

JH The theory and application of fuel air explosions

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The theory and applications of fuel-air explosions

L6 - ACDA6008 Scientific Principles of OME Design

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1. Abstract

Through the exploration of the fuel-air explosive phenomena, the effect of its powerful blast waves in structural and personnel defeat has been explored through a comparison to conventional explosives. Optimised burst and ignition timing allows for a stoichiometric fuel-air ratio to be achieved whilst also utilising the effect of reflected blast waves and Mach stems. An important distinction between fuel-air and conventional explosives is that the former only carries its own fuel and utilises the air at the target area as its oxygen source.

The legality and ethicality of the use of fuel-air explosives is often in question as they often provide a large destructive area that can result in indiscriminate use that regularly causes significant civilian casualties and damage. Accidents have also occurred through the fuel-air explosive phenomena such as the Flixborough chemical plant disaster where a leaking piped caused a large vapour cloud to form as cyclohexane mixed with the air. As the cloud grew and found an ignition source, an explosion occurred that could be heard 30 miles away which killed 28 workers and injured a further 36.

2. Introduction

This paper aims to explore the fuel-air explosive phenomena, the history of its use and its performance in different military environments. These explorations will be used to determine the relevant and efficient applications for fuel-air explosives. A comparison to conventional explosives will describe the key differences between the two explosives types and the effects they can produce.

2.1 Conventional explosives

An explosive is a munition with an energetic component or filling. This filling is capable of producing gas through a chemical reaction with sufficient temperature, pressure and speed to cause damage to the munition's surroundings [1].

TNT is used as a base for comparisons of explosive power, known as an explosive's TNT equivalence. It is worthy of the explosive definition as two moles of TNT (454g) reacts to form 15 moles of hot gases and carbon with a 1000 fold increase in volume.

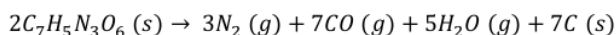


Figure 1 - TNT decomposition reaction

As the material burns it produces the following substances that have strong bonds: CO, CO₂ and N₂. These release a large amount of energy during formation. Through the detonation process, TNT is able to release this energy with a high velocity over a short period of time, contrary to the deflagration process where energy is released over a longer period of time [2].

The oxygen balance of an explosive reaction will determine the products that can be formed. This is defined as the amount of oxygen as a weight percent that is liberated as a result of the complete conversion of the explosive material into oxidised compounds [1]. A negative oxygen balance describes a reaction where there is an insufficient amount of oxygen and incomplete combustion can occur, an example is TNT which is a commonly used conventional explosive. This reaction would rely upon oxygen that is external to the compound even though conventional explosives are designed to carry both their own fuel and oxidiser.

The heat of explosion (Q) is defined as the difference between the energy of formation of the reactants and the energy of formation of the products in a reaction [3]. The Q value of TNT is $4 \times 10^6 J kg^{-1}$ [4] which is used in comparisons with other explosives, another form of TNT equivalence.

Stable explosive compounds require energy to be supplied to them to be initiated, this quantity is known as the initiation or activation energy. Detonators are often used to provide more energy than required by the activation energy to ensure reliability in firings and to increase the rate of reaction [5]. A shock wave develops inside the detonator that is transferred into the main explosive causing it to develop a burning front and also detonate itself.

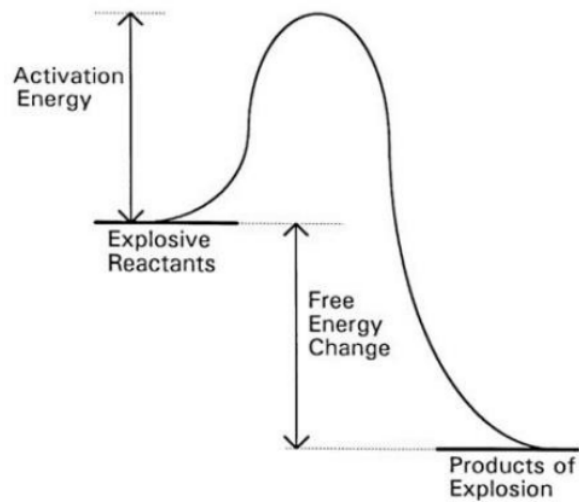


Figure 2 - Explosive reaction profile [5]

Figure 2 depicts the explosive reaction occurring when the added energy reaches the activation energy. Typically explosives undergo exothermic reactions where the products have less energy than the reactants which means energy is released (labelled as “Free Energy Change” in the diagram). This release is observed in the form of heat, pressure and gas generation.

3. Fuel-air explosion theory

Fuel-air explosives, also known as thermobaric bombs, consist of a fuel container, a burster and an ignition device. They are launched as a rocket or dropped as a bomb from an aircraft. The first explosive charge (the burster) is used to break open the container and disseminate the fuel inside, creating a cloud or mist. The cloud can penetrate unsealed buildings and defences as it spreads. A second charge or igniter is used to detonate the cloud resulting in extreme thermal energy in the form of a fireball, a high power blast wave and then a vacuum that sucks in the surrounding oxygen [6]. The second charge can either generate a flame using a spark gap or glow wire which leads to detonation in the fuel-air mixture or a shock wave can be generated using a detonator that causes instantaneous detonation in the mixture [7].

Optimum blast is provided when a stoichiometric mixture is provided. A poor mixture, either fuel rich or fuel lean, will still produce an explosion up to a point. These limits are the Upper Explosion Limit (UEL) and Lower Explosion Limit (LEL). Methane has a heat of explosion of $5 \times 10^7 \text{ J kg}^{-1}$ and explosion limits of 5-14%, meaning between 5 and 14% of the fuel-air mixture can be Methane.

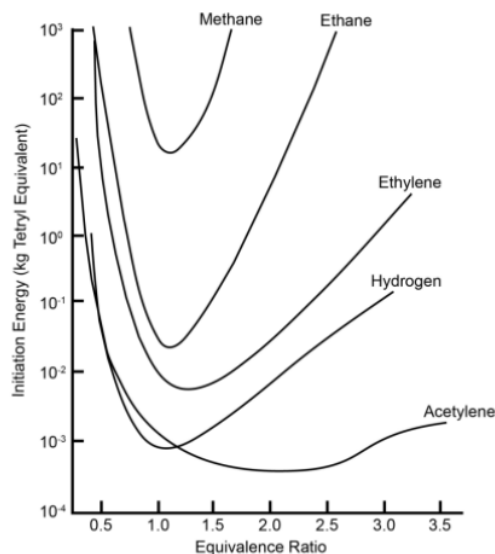


Figure 3 - The effect of initiation energy on the LEL and UEL of Methane

Figure 3 describes the relationship between the initiation energy and the explosive limits of Methane. At higher initiation energies, the LEL decreases and the UEL increases, offering a wider range of initiation energies. At 1J the explosive limit range is 9% and at 10,000J the range increases to 14% [1]. A fuel-air explosive mixture will become more likely to detonate as the initiation energy increases and as the mixture approaches stoichiometry.

3.1 Development

Efforts to develop blast waves with a higher impulse led to findings that fuel-air explosives could be formed from hydrocarbon oxides mixed with air. "These systems yield very high impulse on detonation due to their higher heats of combustion and greater specific volume" [7]. The heat of explosion of fuels used in fuel-air explosives are an order of magnitude higher than TNT however an efficiency factor has an effect. The high heat of explosion is only relevant when there is a stoichiometric quantity of oxygen in the mixture and due to the air containing 3.7x more nitrogen than oxygen by mass, the system is diluted and heat will be absorbed, resulting in a 40% efficiency. However, a TNT equivalence of ~4 is still achieved [1].

A major downside to fuel-air explosive munitions is that the two-stage initiation system is more complex than conventional explosive munitions. The next development for these munitions would be to use a single stage initiation system. This could be achieved by simultaneously dispersing the fuel and an initiation chemical catalyst that takes the appropriate time to ignite the mist, serving as the delay usually provided by the burster and igniter system. An example of this uses gaseous pyrophoric fuel, dimethyl zinc and oxy-acetylene [7].

3.2 Blast waves

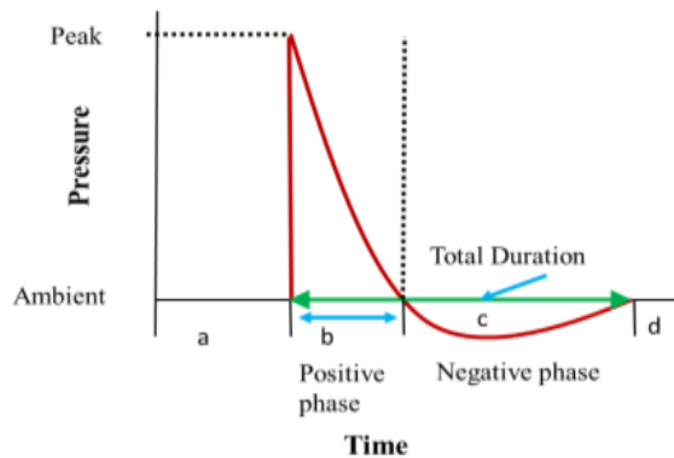


Figure 4 - Characteristics of a shock wave [8]

Impulse is described as the area underneath the curve during the positive phase on a pressure-time graph [1]. Conventional explosives tend to have a higher peak overpressure than fuel-air explosives however, smaller impulses. Impulse is often used to describe the damage potential of a blast wave rather than the peak overpressure as the duration of the pressure has a large effect on the damage dealt to a target.

Blast waves are generated by explosives when they detonate and radiate outwards from the munition. Controlling the location of the detonation in space can alter the effect and potency of the waves. Having an explosive detonate closer to the target results in more damage as the wave is less attenuated due to travelling a smaller distance and expanding less. The height above the ground at which an explosive is detonated is another factor that attributes to the damage potential.

The negative phase duration and amplitude is also larger for fuel-air explosives, this means a strong vacuum like effect is experienced that can create flying debris and is extremely effective against personnel, both by the pulling force experienced and the negative pressure. This can cause barotrauma where the lungs collapse.

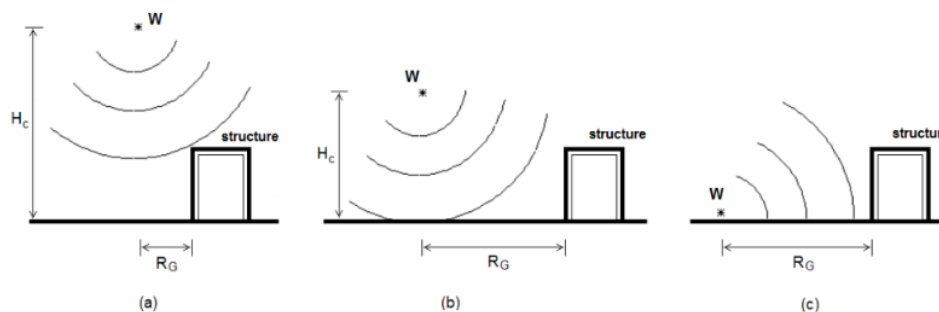


Figure 5 - Types of external explosions [9]

Within Figure 5, graph (a) shows a free-air burst explosion. It is detonated in the air and the blast wave impacts the structure directly with no prior interactions. Graph (b) again shows an air burst but the wave interacts and reflects off of the ground before the structure. This creates a phenomena known as Mach stems that will be described in 3.2.1 Mach stems. In graph (c) the detonation occurs when the charge is on the ground which generates blast waves that radiate hemi-spherically outwards and towards the structure.

The reflection of blast waves off of a rigid structure actually increases the peak pressure it can impart on a target. Air burst detonations are often chosen due to this as they allow the blast wave to reflect before hitting the target. As the wave propagates, it moves the particles of air along its path which collide with the surface. In an ideal linear scenario the reflected pressure would equal the incident pressure and the acting pressure would be doubled, however strong blast waves or shock waves act non-linearly and the reflected particles are obstructed by more particles which leads to a much higher reflected pressure value [9]. This is often several times larger than the incident blast wave.

3.2.1 Mach stems

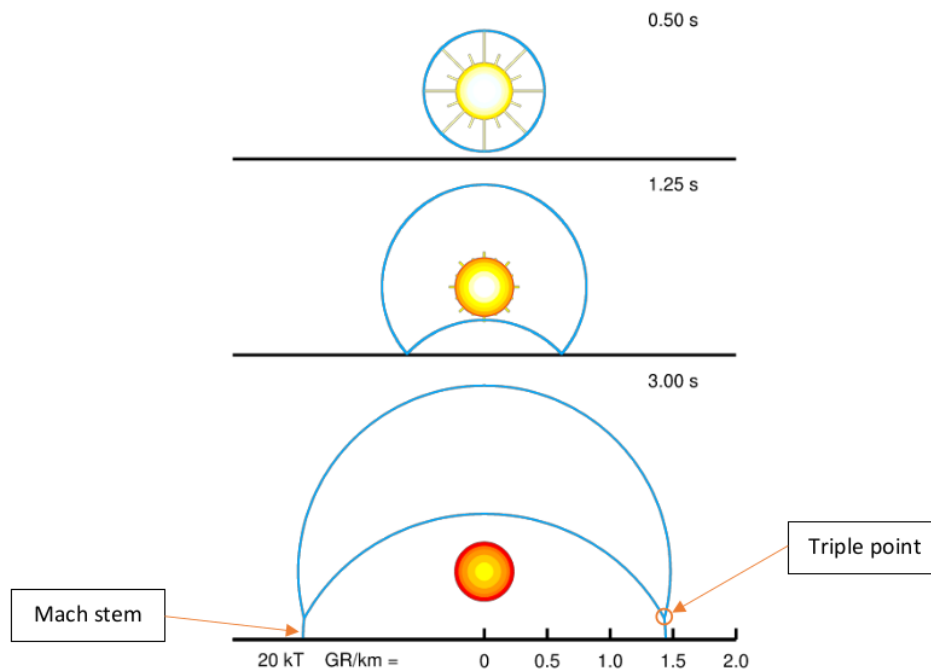


Figure 6 - Air burst blast wave reflection and Mach stem generation [10]

Figure 6 depicts an air burst munition being initiated above the ground, the formation of the blast wave and the reflection of the wave off of the ground. In the third section, a Mach stem has been formed where the initial wave has coalesced with the reflected wave, resulting in the more vertical line. From this an expanded “kill zone” is developed and the downward force on the earth can also collapse tunnels and explode mines below the surface [10]. A triple point is formed at the boundary between the incident wave, the reflected wave and the Mach stem. Targets exposed to the wave between the Mach stem and the triple point experience peak pressures several times higher than the original blast wave. This effect is also utilised in nuclear weapons as 50% of the energy in a

nuclear explosion is output through the blast wave, meaning that incredibly strong waves can be generated from an air burst [11].

4. Ethicality and incidents

Fuel-air explosions impact a wide area, making them prone to indiscriminate use. This is an issue in or around populated areas. In scenarios where military targets are 'dug in' in a town or city, it would be impossible to limit the destructive effect of a fuel-air explosion. Civilians would not be able to taken shelter from its effect due to its effectiveness against personnel, fortifications and buildings, all commonly found in populated areas.

As thermobaric weapons are not related to incendiary weapons, they are not explicitly banned under the Hague or Geneva conventions. However questions arise in the principles of warfare such as the principles of distinction, proportionality, military necessity and humanity where the use of such weapons aren't prohibited but rules can be violated based on context and the manner of their use. Current use in the Ukraine war has brought about these questions again as even if munitions were aimed at military targets, there has been a large number civilian casualties and infrastructure damage [12].

4.1 Incidents

On the 1st of June 1974, an explosion occurred at a chemical plant that produce caprolactam, a chemical used in nylon manufacture. A crack was discovered in one of the reactors prior to the explosion and a bypass pipe was installed to keep the facility running. The new pipe ruptured and cyclohexane (a chemical solvent) leaked from the pipe in a huge quantity. This formed a large vapour cloud that found a source of ignition in the plant where the explosion destroyed almost the entire plant. 18 fatalities occurred due to the roof collapsing and the windows shattering in the control room. A further 10 workers were killed and 36 others were injured on site and additional injuries and damage occurred outside of the facility [13].

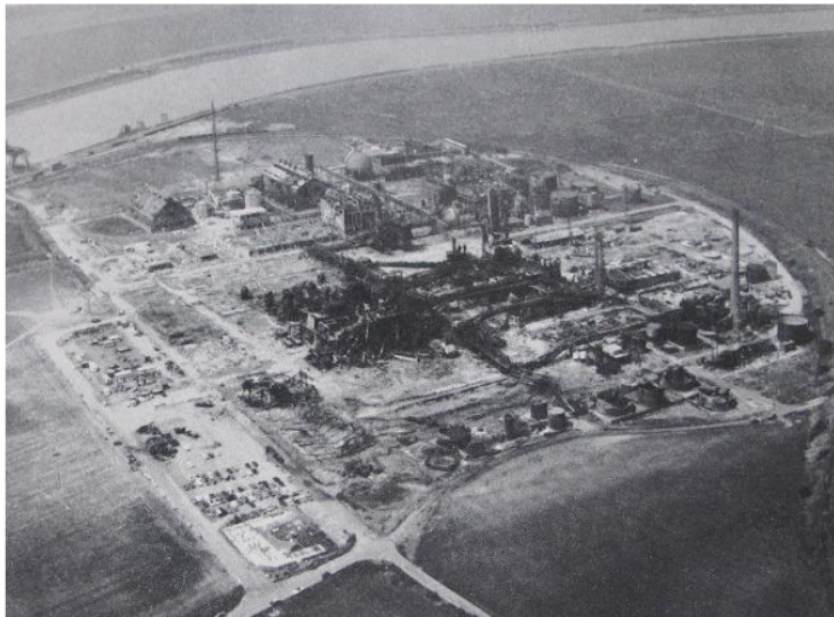


Figure 7 - The Flixborough plant after the explosion

5. Military environment applications

Explosive power is regularly harnessed in a variety of military applications, however this section will explore how fuel-air explosives will perform against a range of targets.

The United States used a newly developed thermobaric bomb, the BLU-118/B, in Afghanistan [14]. Starting off as the Guided Bomb Unit-28 (GBU-28) which was developed to penetrate hardened, underground command centres, the filling was exchanged for a thermobaric explosive fill. This allowed the penetrating warhead to still breach deep into structures but also deliver higher and sustained blast pressures in confined spaces such as tunnels and underground facilities [15].

5.1 Armour defeat

Due to the nature of fuel-air explosive munitions not being able to supply their own oxygen, fuel-air explosives are not applicable to be used underwater against targets such as a ship hull. In this scenario, conventional explosives are used to defeat maritime armour effectively.

Similarly, a fuel-air munition's performance against a heavy vehicle's armour would pale in comparison to a conventional explosive munition such as a shaped charge. As stated before, although the impulse is larger from fuel-air explosions, the peak overpressure is lower and that is the driving factor in defeating the armour using solely the blast wave. A secondary effect of the fuel-air munition is the large fireball that is produced, this would have little effect on an armoured target but would be very effective against light skinned vehicles.

5.2 Structure defeat

The immense blast wave generated by fuel-air explosives proves effective in structural defeat applications. The blast waves can destroy unreinforced buildings and kill personnel in enclosed spaces such as caves, buildings and bunkers [16] [12].

Using the Beirut Explosion as an example, where the equivalent of 1,039,500kg TNT detonated, near complete destruction of houses occurred up to 600m away from the blast and steel towers were blown down up to 230m away [17].

5.3 Personnel defeat

As conventional explosives' blast waves are effective against personnel, the empowered fuel-air blast waves are even more harmful and take effect on the pulmonary, cardiovascular, auditory, gastrointestinal and central nervous systems by inducing shear forces on air/tissue interfaces. The respiratory system or pulmonary system is affected by the blast wave causing fluid to leak into the lungs as they rupture. Blood clots can be formed in the heart or coronary arteries and haemorrhaging can occur. Bruising or perforation can occur in the gastrointestinal system where the stress wave crosses pockets of gas in the bowel. Death or deterioration of function can occur from a cerebral arterial embolism (blocked artery) in the central nervous system [14].

The cloud of combustible material is dispersed rapidly around the target area causing the surrounding area to be burnt due to an intense fireball [18]. Additionally the collapse of structures can crush and flying debris can kill personnel [16].

5.4 Counter-mobility obstacles

The first fuel air explosives were used to clear minefields and potential helicopter landing areas. The Cluster Bomb Unit (CBU) 55/B (Figure 8 below) was developed after witnessing extensive use of cannisters of Ethylene Oxide in Vietnam in 1967. The 340kg cluster bomb contained three BLU-73A/B sub munitions that contained propane and a delayed igniter [19].



Figure 8 - CBU-55 fuel air explosives bombs in south Vietnam, 1970

6. Conclusion

In conclusion, fuel-air explosions are a type of explosive phenomenon that occurs when a fuel source is mixed with a high concentration of air and then ignited. This type of explosion is known for its immense destructive power, due to the increased impulse, positive phase duration and negative phase duration over conventional explosives. Another important distinction is that fuel-air explosives only carry a fuel on board and utilise the air at the target to create a stoichiometric detonation reaction.

These munitions are utilised for their intense blast waves that can be optimised by using an air-burst initiation where the reflected blast waves combine with the incident wave to form even more powerful waves. In military applications fuel-air explosives provide an efficient method of structure defeat through the spreading of the fuel into tunnels, caves and building openings and intense damage to personnel through blast injury, the vacuum effect and incendiary damage. Mine and landing site clearing has also been achieved using the blast waves from these munitions.

However, the legality and ethicality of the use of fuel-air explosives is always in question as they can have a large target area that can result in indiscriminate use that regularly causes significant civilian casualties and damage to non-military targets.

7. References

- [1] S. G. Murray, JSP 333 Services Textbook of Explosives, Ministry of Defense, 2020.
- [2] A. Streitwieser and C. H. Heathcock, Introduction to Organic Chemistry, New Jersey: Prentice Hall, 1992.
- [3] R. A. Fifer and B. J. Morris, Techniques for the Estimation of, Army Research Laboratory, 1993.
- [4] Y. Zunger, "On meteors, TNT, swallows, and the end of the world," Scientific American, 15 April 2013. [Online]. Available: <https://blogs.scientificamerican.com/guest-blog/on-meteors-tnt-swallows-and-the-end-of-the-world/>. [Accessed 4 December 2022].
- [5] J. Akhavan, The Chemistry of Explosives, RSC Publishing, 2011.
- [6] BBC News, "What is a thermobaric or vacuum bomb?," 10 March 2022. [Online]. Available: <https://www.bbc.com/news/business-60571395>. [Accessed 7 December 2022].
- [7] A. Appa Rao, "Fuel Air Explosives," *Defence Science Journal*, vol. XXXVII, no. 1, pp. 23-28, 1987.
- [8] B. Rutter, "Pressure versus impulse graph for blast-induced traumatic brain injury and correlation to observable blast injuries," Scholar's Mine, 2019.
- [9] V. Karlos and G. Solomos, "Calculation of Blast Loads for Application to Structural Components," Joint Research Centre, Luxembourg, 2013.
- [10] R. Letzer, "Here's why the 'mother of all bombs' exploded 6 feet above its target in Afghanistan," Business Insider, 13 April 2017. [Online]. Available: <https://www.businessinsider.com/moab-airburst-bomb-explanation-2017-4?r=US&IR=T>. [Accessed 11 12 2022].
- [11] P. P. Craig and J. A. Jungerman, The Nuclear Arms Race: Technology and Society, McGraw-Hill College, 1990.
- [12] A. Sharma and C. S. Agarwal, "Using Environment as a Weapon: The Case of Vacuum Bombs," *OpinioJuris*, 14 September 2022. [Online]. Available: <http://opiniojuris.org/2022/09/14/using-environment-as-a-weapon-the-case-of-vacuum-bombs/>. [Accessed 12 December 2022].
- [13] M. Dunton, "Flixborough, 1 June 1974," *The National Archives*, 2014 May 2014.
- [14] D. Andrew, "Thermobaric Munitions and their Medical Effects," *Journal of Military and Veterans' Health*, vol. XII, no. 1, 2003.
- [15] National Research Council, "Conventional Weapons," in *Effects of Nuclear Earth-Penetrator and Other Weapons*, Washington, DC, National Academic Press, 2005, pp. 99-102.
- [16] Human Rights Watch, "Chechnya Conflict: Use of Vacuum Bombs by Russian Forces," 1 February 2000. [Online]. Available: <https://www.hrw.org/news/2000/02/01/chechnya-conflict-use-vacuum-bombs-russian-forces>. [Accessed 11 December 2022].

[17] G. Collet, "Case Study - Beirut," University of Wales Trinity Saint David, 2020.

[18] L. Türker, "Thermobaric and enhanced blast explosives (TBX and EBX)," *Defense Technology*, vol. XII, no. 6, pp. 423-445, 2016.

[19] A. Smith, "Flixborough goes bomb in Vietnam," *New Scientist*, vol. LXVI, no. 947, p. 262, 1975.

JH The theory and application of fuel air explosions

GRADEMARK REPORT

FINAL GRADE

64/100

GENERAL COMMENTS

Instructor

James,

James,

You demonstrated a good understanding of FAE and its applications in the military context. Please see my detailed observations below:

1. Consider a peer review to eliminate some minor grammatical errors - see second paragraph of abstract where you have The the.

2. Consider a reference to support your statement on legality in use. FAE is not, actually, in contradiction to LOAC if the user considers military necessity, proportionality, distinction and humanity. Not a nice way to die but.....

3. I liked the way you orchestrated the journey through the assignment, first starting with conventional explosives and their contrast with FAE.

4. Q is determined using Hess' Law. This would have been easier to state.

5. FAE are not also known as thermobaric bombs since the science is different. This is a media

misconception so be careful. By way of edification, consider the following:

A fuel-air explosion differs from that created by a conventional explosive in that the fuel elements do not carry their own oxygen. For an explosion to occur, fuel must be mixed with ambient atmospheric air, and when mixing is complete, be initiated by a delayed ignition source. Delayed ignition is required in order that the fuel can mix appropriately with the air. Fuels involved take the form of gases, vapours, aerosolised liquids or particulate dust clouds. There are also the Upper and Lower Explosion Limits (UEL/LEL) to consider for gas/vapour/air and dust/air mixtures since most fuels in military applications are dispersed with a central burster charge, producing a cloud of droplets or particulates that mix and are then detonated by a secondary initiation source about 0.5 – 1.0 s later. Concentrations can vary considerably in the cloud at time of secondary initiation, which lends to the use of fuels with a wide range of UEL and LEL. Two-phase initiation with FAE adds complexity and the attraction of a thermobaric system is that it requires no separate secondary means of initiation. As such, it can be used reliably. The fuel consists of a monopropellant and energetic particles (particles with high heats of combustion such as beryllium, boron, lithium, aluminium, magnesium, zinc or sulphur). In terms of functionality, a bursting charge is still required but in this instance disperses an explosive slurry, which then explodes to achieve the desired blast effect. The mechanism works as follows (and can be considered two-stage): firstly, anaerobic action (without air oxygen) occurs inside a conventional high explosive core in microseconds; then aerobic delayed burning action of the fuel-rich outer charge, which depends mainly on the consumption of the surrounding air and which results in an intense fireball (5000 °C+) and high blast overpressure. The fuel can rapidly diffuse within structures, consuming the oxygen and creating conditions that make human survivability extremely unlikely (heat, flame and barotrauma to the lungs)

6. Good use and explanation of Figure 3. You basically want a broad LEL and UEL so that minor changes in mixing ratio do not overly affect the explosion.

7. Consider using a diagram to illustrate the basic construct of a FAE munition - casing, central burster, primary and secondary initiator, payload etc.

8. For armour, consider how FAE would impact on DAS and ERA.

9. Bunkers etc good, but Beirut was not FAE. It was the deflagration to detonation of ammonium nitrate.

10. For personnel defeat, what overpressure are we talking about - 150 - 250 PSI.

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