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INVENTORY OF DOCUMENTS
FOIA 92-FOI-0349/2264/2265/2266/2267/2399

DOC #1 - EXTRACT FROM "MILITARY TECHNOLOGY 9/89" TITLED "FUEL-AIR EXPLOSIVES, WEAPONS, AND EFFECTS"	RELEASABLE
DOC #2 - MEDIA ARTICLES - VARIOUS ORIGINATORS	RELEASABLE
DOC #3 - COPY OF "STAR TRIBUNE" NEWSPAPER ARTICLE, DEC 16, 1990, TITLED "HONEYWELL SAYS BOMB DATA SALE VIOLATED POLICY"	RELEASABLE
DOC #4 - HONEYWELL, OPERATIONAL ANALYSIS, AEROSPACE & DEFENCE, NOV 84	RELEASABLE
DOC #5 - MEMORANDUM FROM DTSA/TSO (SWANSON) TO DIA (MR. J. DEARLOVE), 25 MAR 92, SUBJ: REQUEST FOR IDENTIFICATION **(CONFIDENTIAL/NOFORN)**	RELEAS/REDACTED (b)(1)
DOC #6 - MEMORANDUM FROM DTSA (CAPT DUECY) TO DIA/DC-4A, UNDATED, SUBJ: COLLECTION REQUIREMENT (U) REQUIREMENT (U) **(SECRET/NOFORN/WNINTEL)**	NONRELEASABLE Sec 1.3 (a)(4)/(5) Sec 1.3 (b)
DOC #7 - DOCUMENT - WORKING CHRONOLOGY FUEL AIR EXPLOSIVES (FAE) IRAQ, ORIG: CAPT JAMES A. HUFF, DTSA **(SECRET/NOFORN)**	RELEAS/REDACTED (b)(1), (b)(7) Sec 1.3 (a)(4) and (5); (b)
DOC #8 - LETTER FROM DUSD/TSP (RUDMAN) TO SENATOR MACK, NOV 20, 1990, CONCERNING IRAQ'S CAPABILITY TO DELIVER FUEL AIR EXPLOSIVES	RELEASABLE
DOC #9 - DOCUMENT, RESPONSE TO CONGRESSIONAL INQUIRY, 30 OCT 90, ORIGINATOR UNKNOWN	RELEASABLE
DOC #10 - MEMORANDUM FROM DTSA/TSO (MALOOF) TO DUSD/TSP DEC 7, 1990, SUBJ: HONEYWELL (U)	REL/REDACT/TRANS
DOC #11 - CONVERSATION RECORD, HONEYWELL AND CAPT HUFF 11 DEC 90, SUBJ: MEETING WITH THREE HONEYWELL REPRESENTATIVES, BONSIGNOR, BURNHART, BURNS	RELEASABLE
DOC #12 - CONVERSATION RECORD, TOBY DARCY (OGC), 22 OCT 92 SUBJ: FOIA	RELEASABLE
DOC #13 - MEMO FROM MARTHA COOPER (ALLIANT TECHSYSTEMS) TO LINDA RANDALL (DTSA), NOV 7, 90,	RELEASABLE
DOC #14 - WORKING PAPER, UNDATED, ORIGINATOR UNKNOWN, SUBJ: HONEYWELL	RELEASABLE

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DOC #15 - DTSA APPOINTMENT REQUEST FORM, 10 DEC 90, SUBJ: HONEYWELL INVOLVEMENT IN IRAQ FAE TECHNOLOGY TRANSFER — RELEASABLE

DOC #16 - DTSA APPOINTMENT REQUEST FORM, 5 FEB 91, SUBJ: PRESENTATION OF HONEYWELL CLOSING INVESTIGATION REPORT ON FAE TECHNOLOGY TRANSFER — RELEASABLE

DOC #17 - HONEYWELL INTEROFFICE CORRESPONDENCE, JAN 21, 91 SUBJ: FAE DATA REVIEW — RELEASABLE

DOC #18 - HONEYWELL INTEROFFICE CORRESPONDENCE, DEC 17, 90 SUBJ: INFORMATION FOR CAPTAIN JIM HUFF, USN/DTSA — RELEASABLE

DOC #19 - HONEYWELL INTEROFFICE CORRESPONDENCE, DEC 7, 90 SUBJ: REQUEST FOR INFORMATION BY DEFENSE TECHNOLOGY SECURITY ADMINISTRATION — RELEASABLE

DOC #20 - LETTER FROM JENNIFER E. CRAWFORD, HONEYWELL CORPORATE COMPLIANCE COUNSEL, TO LT FREDERICK C. VOLLKOMMER, DTSA/TSO, DEC 7, 90 — RELEASABLE

DOC #21 - HONEYWELL INTEROFFICE CORRESPONDENCE, FEB 7, 91 SUBJ: FAE REPORT ASSESSMENTS — RELEASABLE

DOC #22 - LETTER FROM AEROSPACE LIMITED, K.G. SMITH, TO HONEYWELL, MR. GRAHAM RUTHEN, SEP 10, 90 — RELEASABLE

DOC #23 - DOCUMENT "REPORT OF INVESTIGATION INTO ALLEGATIONS OF TRANSFER OF HONEYWELL WEAPONS TECHNOLOGY TO IRAQ — RELEASABLE

DOC #24 - FAE WARHEAD ANALYSIS - FINAL REPORT, DEC 84 — RELEASABLE

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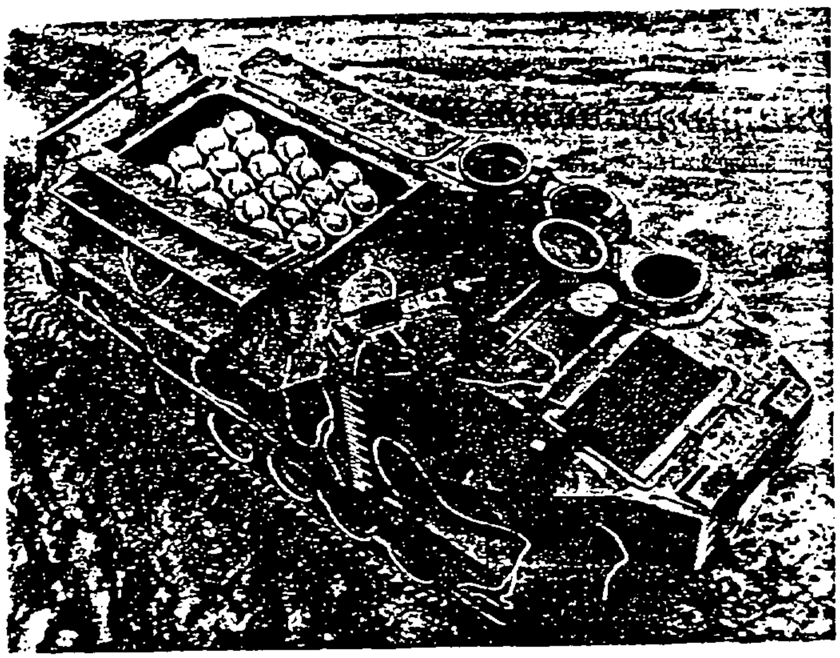

The latest operational application of FAE is the CATFAE (Catapult-Launched FAE) mine-clearing system, currently under development for the USMC.

Louis Lavoie

Fuel-Air Explosives, Weapons, and Effects

A fuel-air explosive (FAE) is, by definition, a detonable material that gets most, or all, of its required oxygen from the air. Two almost unique properties of FAE are that it carries little or no oxygen with it, thereby giving it good weight efficiency, and that the detonation occurs over a significant area thereby generating a greater impulse than with a point detonation characteristic of conventional high explosives. Exceptions to the latter point, that will not be discussed in detail here, are dispersed, conventional high explosive powders, and nuclear explosives.

Reports of Soviet use of FAE in Afghanistan have revived interest in FAE weapons by the US military after several years of relative neglect. The zenith of US development may have been reached in January 1973 with the detonation of an FAE device next to the decommissioned destroyer escort, USS MCNULTY, which eventually caused it to sink. However, at least 13 years earlier work was in progress at the China Lake Naval Weapons Center which, by the late 1960s, led to operational tests in Vietnam and the design of the CBU-55/B containing 3, BLU-73/B FAE bombs. Since the late 1970s interest in FAE weapons has declined except for the CATFAE minefield clearing system and the stillborn SLUFAE, also intended for mine clearing. What are fuel-air explosives, how do they work, and why have they alternately excited and disappointed the military community? In this article we will try to answer these questions as well as address the issues of weaponisation, and tactical application

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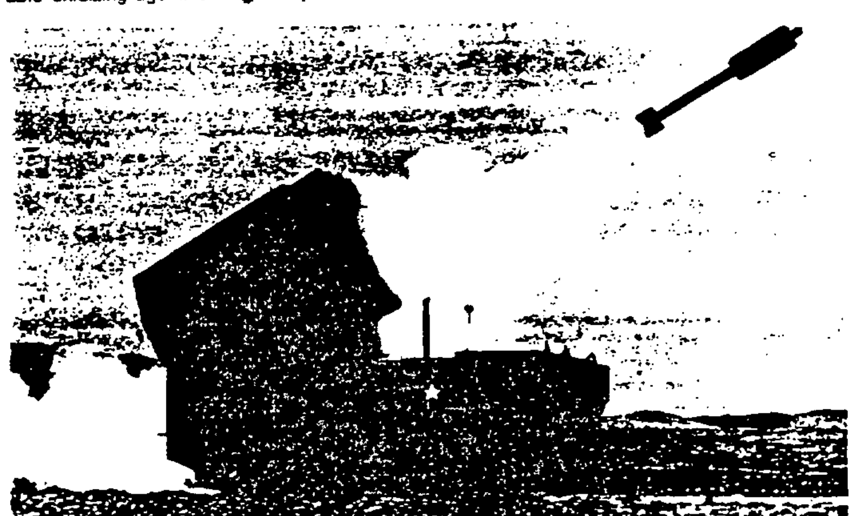
Technical Background

Precisely as the name implies, fuel-air explosives are explosives that rely on oxygen in the air as the primary source of the indispensable oxidizing agent. Several early references in the literature otherwise, are incorrect. For example, FAE detonation in space is a contradiction in terms. Other early references to FAE "burning" in an oxygen-free environment are beside the point, since "burning" and "detonation" are not the same thing. Burning is "slow" oxidation (rusting iron is even slower yet) while detonation is very quick, propagating through the reacting medium at velocities of several kilometres per second.* The fuel-air explosion process contrasts to that of conventional high explosives, such as TNT, which carry adequate oxygen already attached to the explosive molecule (Figure 1). It should be noted, however, that the energy output of conventional high explosives can be boosted by adding oxidizer if their molecules are naturally oxygen lean (TNT), or by adding a reducing agent such as aluminum, if fuel lean (ammonium nitrate). In some cases the additional oxidizer can come from the air just as with FAE. Indeed, some of these explosives, when dispersed as powders, are coming to be grouped with FAE and other high impulse explosives under the name of enhanced blast munitions (EBM).

Fuel-air explosives are more weight efficient than conventional explosives since they obtain their oxygen from the air. Figure 1 shows that 42 % of the weight of TNT is due to the oxygen it must carry with it while 41 and 47 % of the weight of the consumables (fuel and oxygen) in, respectively, propylene oxide/air or aluminum dust/air explosions, comes from the

** Some FAE fuels, for example ethylene and propylene oxides, have an oxygen atom in the molecule and, indeed, can exothermally decompose in the absence of air, but they don't detonate. Also contrary to some references in the defence literature, many FAE fuels are relatively benign e.g. kerosene.*

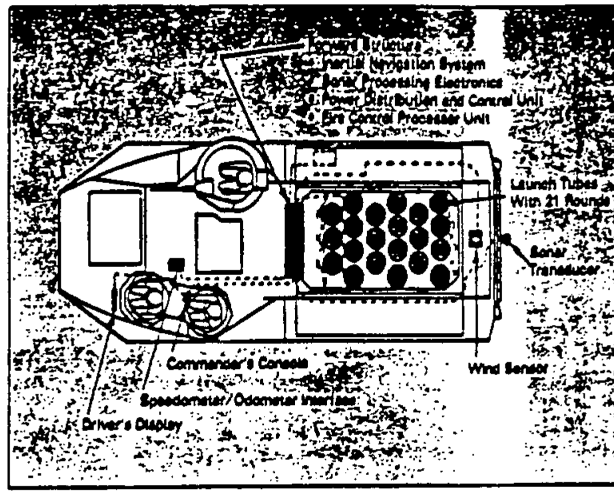
SLUFAE was an earlier US attempt at FAE for mine-clearing purposes.



air and is not carried with the explosives. Accordingly, weight for weight propylene oxide and aluminum release 7.9 and 7.4 times as much energy as TNT (Table I).

There are many possible FAE fuels, but practical onsiderations such as safety quickly reduce the list. The unclassified list of known detonable FAE fuels is not very large. Hydrocarbons are the most numerous. Table II lists some of those that have been demonstrated to detonate as well as including non-hydrocarbon fuels. Indeed, hydrocarbons attracted early civil attention to the FAE phenomenon because of accidents in the petroleum industry.

Arrangement of a CATFAE vehicle (AAVP-7A1 hull).



Below: Fig. 1: Idealised chemical reactions of exploding TNT and FAE fuels.

100 kg TNT:

$$12\,C_6H_2CH_3(NO_2)_3 \rightarrow 14\,CO_2 + 24\,CO + 46\,C + 17\,N_2 + 20\,H_2O + 7\,H_2 + 2\,NH_3$$

42 kg O_2

100 kg Propylene Oxide:

$$C_3H_6O + 4\,O_2 \rightarrow 3\,CO_2 + 3\,H_2O$$

69 kg from the air

100 kg Decane:

$$2\,C_{10}H_{22} + 3O_2 \rightarrow 20\,CO_2 + 22\,H_2O$$

34 kg from the air

100 kg Aluminum Powder:

$$4\,Al + 3O_2 \rightarrow 2\,Al_2O_3$$

89 kg from the air

Fuel	kcal/g	kcal/cm³
Decane	11.3	8.5
Kerosene	10.2	8.2
Propylene Oxide	7.9	6.6
Aluminum (powder)	7.4	11*
Ethylene Oxide	6.9	6.0
TNT	1.1	1.6

*Although elemental aluminum has a density of 2.7 the bulk powder densities are significantly less, typically in the range of 0.8 to 1.5 g/cm³.

Table I: Specific energy of some FAE fuels.

No theory of detonation exists that can predict the detonability of a potential FAE material. Many fuels will burn (deflagrate) without detonating. Others will only detonate if suitably excited by a powerful enough source, and some will detonate quite easily. The critical detonation energy depends on the type of fuel, the fuel particle or drop size if it is solid or liquid, the energy deposition rate (power), the fuel-air ratio, and, to a lesser extent, the temperature and humidity. A useful rule of thumb is that an FAE detonator should contain a conventional explosive mass about 1 % of the FAE mass.

FAE as Weapons

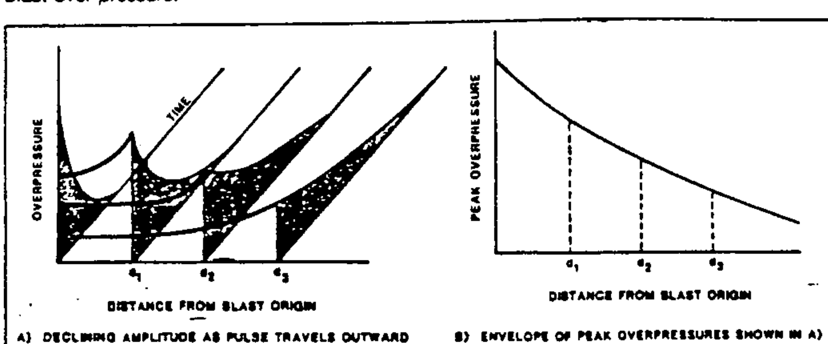
The weaponisation of fuel-air explosives would be greatly simplified if a good way could be found to cause the fuel to self detonate at the right moment. Thus far research in this area has been only slightly successful with fairly impractical results achieved by injection of highly reactive fluorine or bromine trifloride into the fuel cloud causing detonation. Some progress is also being made with autodetonating gelled fuels.

Apart from nuclear weapons, pure blast weapons are believed by some in the defence community to be relatively ineffective unless augmented with penetrators, fragmentation, incendiary, or other damage-producing agents. Nevertheless, FAEs are effective precisely because of their blast. To understand this apparent contradiction it is necessary to use more exact terms than "blast" and to relate these new terms to target vulnerability.

The blast produced by any explosive can be characterised by peak overpressure and impulse* at a given distance from the centre of the detonation. Overpressure is the pressure increase above normal ambient caused by the heated and expanding products of the explosive chemical reaction. At a point some distance from the blast origin the passing blast wave will cause the pressure to abruptly increase from ambient to some peak value, then decay relatively slowly back to ambient. The greater the distance from the origin of the blast, the less the peak overpressure of the passing wave (Figure 2). Impulse at these same measurement points is the product of the overpressure and the duration of its application. If the overpressure occurred as a square wave, the impulse would be calculated as just overpressure times its duration. But overpressure decays exponentially, so its waveform appears more triangular than square. Accordingly, an exact expression for impulse requires the time integration of overpressure (I = ? P dt.) However, in some cases it is adequate to assume the overpressure pulse is shaped like a right triangle and compute the impulse as the area of the triangle (I = 0.5 Pt)

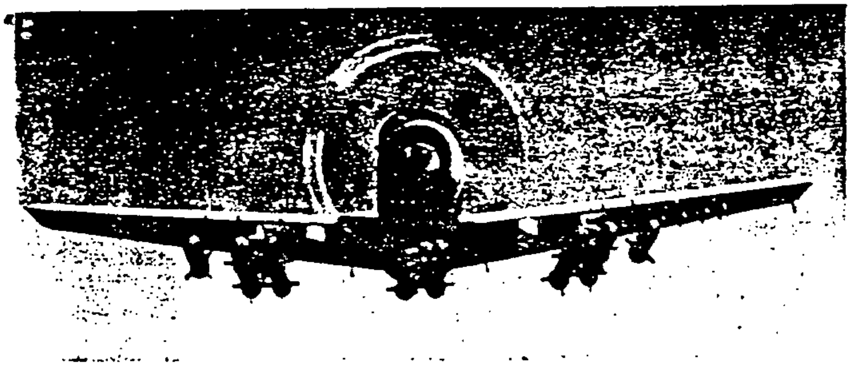
* *The term "impulse," is used here as it is generally used in the blast and vulnerability literature, which is strictly speaking, impulse per unit area. Of course, true impulse is the time integral of force.*

Fig. 2: Pulse shape in space and time of blast over pressure.



A) DECLINING AMPLITUDE AS PULSE TRAVELS OUTWARD FROM ORIGIN

B) ENVELOPE OF PEAK OVERPRESSURES SHOWN IN A)



Above: This Vietnam-era photo depicts a SKYRAIDER carrying 14 CBU-55/B FAE bombs.

where "t" is the decay time constant. There are several factors that establish the duration of the overpressure pulse, and hence the impulse, including the quantity, energetics, spatial distribution of the exploding material, and the distance from the centre of the explosion. Useful approximations for computing FAE overpressure and impulse are given in Table III.

Blast waves load targets through diffraction and drag coupling. Targets are damaged in diffraction loading because of the pressure differences that appear across them as the blast wave passes. The coupling is optimum when the blast wave duration is less than one fourth the natural vibration period of the target. Lightweight targets have short periods. This implies short, high-pressure blasts are needed to damage them, since the period is proportional to the square root of the target mass. Accordingly, diffraction-dominated coupling is most effective against overpressure sensitive targets

Acetylene
Aluminum
Butane
Decane
Ethane
Ethylene
Ethylene Oxide
Heptane
Kerosene
Methane
Propane
Propylene
Propylene Oxide

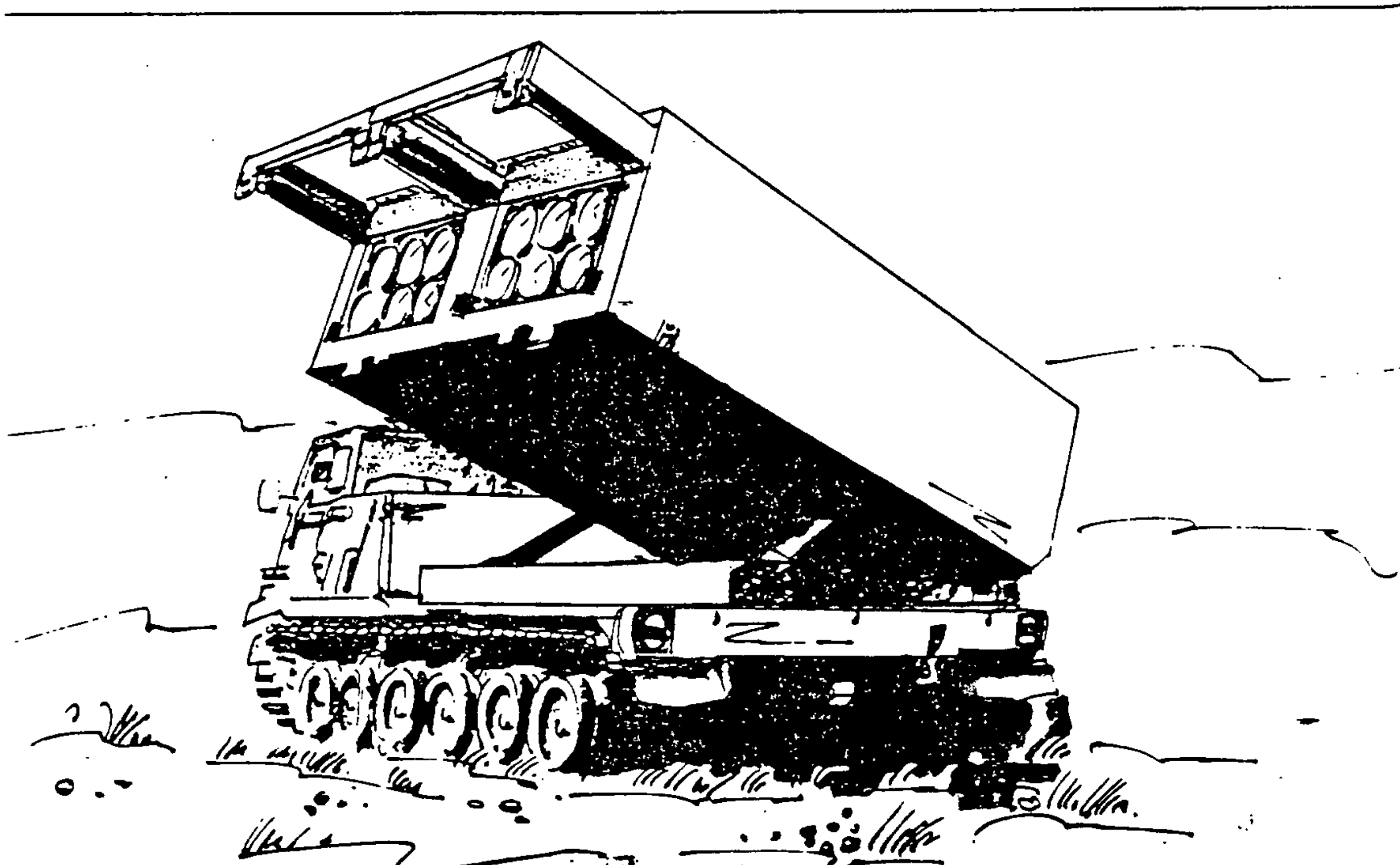
Table II: Some possible FAE fuels that have been successfully detonated.

Targets are damaged by drag loading because of the drag resistance to the air moving rapidly over them. Drag load damage increases in proportion to the duration of the blast. Since impulse is the product of overpressure and time, it is clear that impulse dominated blast loading is most effective against drag-sensitive targets. Drag-sensitive targets are usually considered "soft," while diffraction-sensitive targets are usually considered "hard" (Table IV).

Many targets are vulnerable to both diffraction and drag loads. For example, an automobile exposed to a blast with its windows closed might have its roof crushed and windows broken by diffraction loads, while its radio antenna is torn off and the vehicle rolled over by drag loads.

FAE weapons, with their relatively long impulse and relatively low blast overpressure, are ideally best matched to soft targets. Aircraft, unreinforced buildings, missiles of all kinds, trucks and other unarmoured motor vehicles, radar and communications antennas, and troops are soft. Lightly armoured combat vehicles, APCs and the like, reinforced buildings, concrete bunkers, artillery, and tanks vary from intermediate to hard, and accordingly may not be suitable FAE targets. However, one should not overlook the possibility of attacking the soft sub-systems mounted on hard targets. For example, tanks and APCs could be rendered virtually useless by destroying their antennas and external stores.

Any target, hard or soft, requires a certain minimum or critical impulse and peak over-



pressure to be damaged. Once having satisfied these minimum requirements any combination of impulse and overpressure will do the job. This information can be very conveniently presented in a P/I vulnerability diagram, as shown in Figure 3a. The curve in Figure 3a separates the vulnerable and invulnerable P/I domains for a given target. Every target has its own curve. The harder the target, the more the curve moves up and to the right, reflecting greater minimum impulse and overpressure for assured destruction. It is often not practicable to calculate the curve, even with a large computer, although it can be computed for some simple systems. The curve is more frequently defined by a combination of experimental and computational techniques.

Figure 3a represents a hypothetical soft structure vulnerability. Figure 3b shows the P/I curves for hypothetical soft and hard structures together with a plot of P and I as a function of blast radius for 227 kilograms of TNT and 227 kilograms of a typical FAE fuel. Figure 3b instantly shows the advantages and limi-

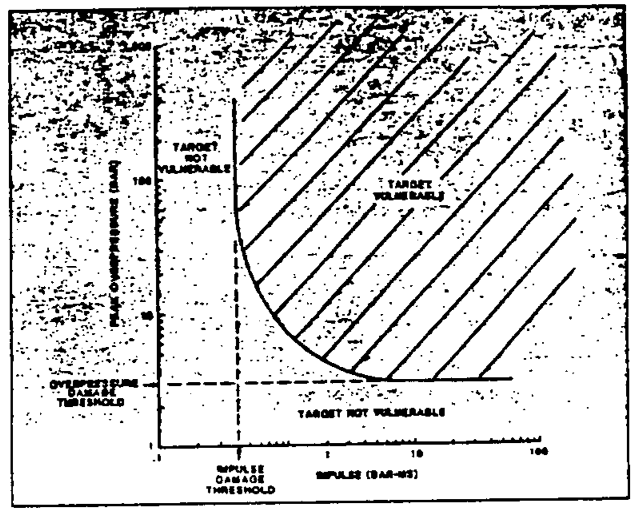


Fig. 3a: Target pressure/impulse vulnerabilivy.

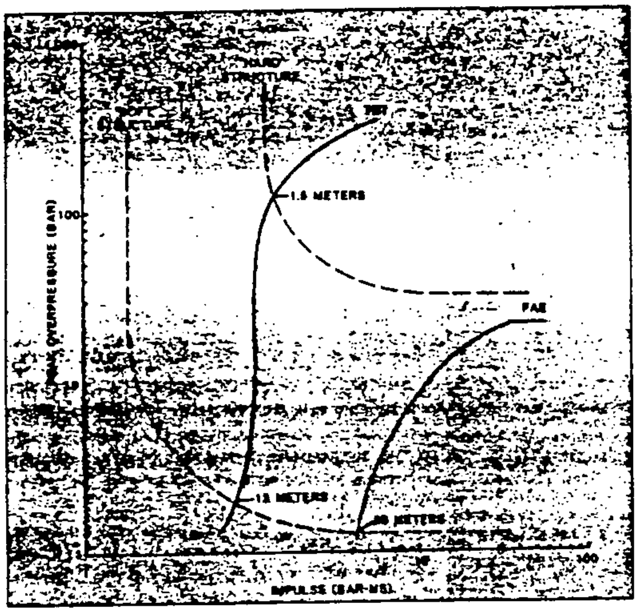


Fig. 3b: Comparison of hard and soft target vulnerability to 227kg of TNT and FAE.

tations of FAE over conventional high explosives. FAE will not destroy the hard structure since the FAE curve and hard structure curve do not intersect. Moreover, increasing the amount of FAE fuel will not help since that merely extends the FAE curve to the right (peak overpressure for an FAE fuel is independent of the quantity of fuel). On the other hand, the FAE and soft structure curves inersect at 30 metres on the FAE curve. This is the lethal radius for this FAE weapon. Compare this to the 12-metre intersection point on the TNT curve. Clearly the lethal radius against this soft structure for 227 kilograms of FAE exceeds that of an equal quantity of TNT by two and a half times.

Table III: FAE blast computation.

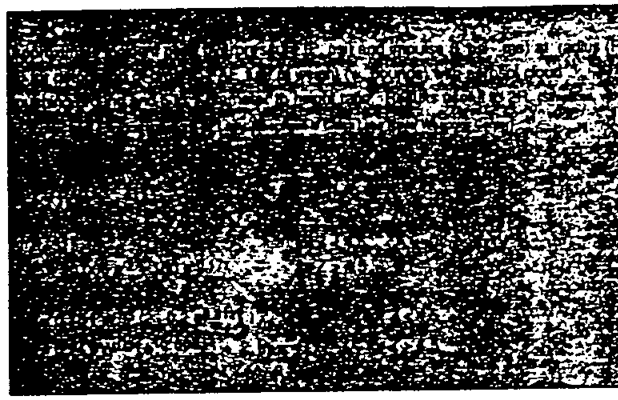


Fig. 4a: Overpressure for 1KT nuclear, TNT, FAE.

Fig. 4b: Impulse for 1KT nuclear, TNT, FAE.

A comparison of overpressure and impulse versus distance for equivalent/equal masses of nuclear, TNT, and FAE explosives immediately reveals the advantages and limitations of FAE weapons (Figure 4a, b). The peak overpressures available in the near field from FAE are substantially less than those of TNT and nuclear weapons. This significantly limits the effectiveness of FAE against hard targets. On the other hand, Figure 4b shows that the FAE impulse is about a hundred times greater than TNT. This gives FAE a much greater effectiveness against soft targets. It is also appropriate here to point out that FAE is not a substitute for nuclear weapons as has sometimes been reported in the literature. It might be used on a small scale to simulate nuclear weapons effects for vulnerability testing, but the quantity of FAE fuel needed to substitute for a tactical nuclear weapon of even fractional kiloton yield does not suggest a very practical device. An FAE weapon with a yield equivalent to a 0.1 kiloton nuclear weapon would weigh 45,000 kilograms and have a volume of 52 cubic metres.

The weaponisation of FAE is dominated by the challenges of creating the proper fuel air mixture and then detonating it at the correct time. A generic FAE bomb (Figure 5) might be a right circular cylinder, two or three diameters long, filled with fuel and fuzed to burst open at a suitable distance above the ground. A burster charge of high explosive, weighing 1 or 2% of the fuel weight, is located in a tube along the bomb's central axis. The purpose of the burster charge is to break open the container and distribute the fuel in a cloud such that the volume of air filled will contain sufficient oxygen for complete fuel oxidization. This volume is determined by the quantity and reaction chemistry of fuel (Figure 1). When the fuel is a liquid the burster charge also serves the purpose of shattering the liquid into a micromist aerosol so that it can be detonated. This is an extremely important and delicate function since the detonability of the fuel is determined, in part, by the aerosol droplet size.

The aerosol is detonated once the cloud reaches the diameter for the optimum fuel-air ratio (also kown as the stoichiometric ratio). The "second event" detonator, like the burster charge, is also a high explosive weighing a few percent of the fuel weight. The reason the burster charge doesn't detonate the fuel while the detonator does, is that the fuel is not in a detonable aerosol form at the "first event." The detonator is ejected from the generic bomb shortly before the burster charge goes off. It is slowed with a suitable drag device so that it enters the aerosol cloud and detonates at the instant of fuel-air stoichiometry. An FAE weapon would be considerably more simple if this obviously very tricky procedure could be avoided by finding some way to get the fuel to self detonate the instant it reaches stoichiometry.

The effects of weather on FAE cloud formation and detonation are not very well known. Apart from some anecdotal data it has been established that temperature and humidity can change the required detonation energy by as much as 10 or 20 %.

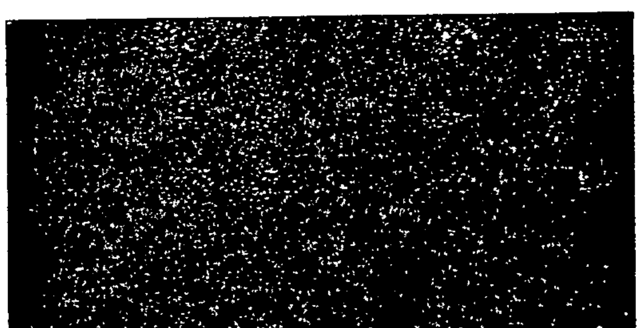


Fig. 5: Generic FAE bomb.

Safety is an important issue in weaponising FAE. Some fuels, such as aluminum powder, are benign, while others may be corrosive, unstable, inflammable, explosive, or toxic. Table V lists a few of these factors for some selected fuels. Sometimes a fuel can be selected to reduce some of these hazards. For example, the high volatility of ethylene oxide makes it difficult to contain safely at elevated temperatures. Propylene oxide is, nevertheless, a somewhat difficult material to handle and store, and could pose a fire hazard if the container leaked. Indeed, liquid fuels, in general,

System	Loading: Diffraction	Drag	Hard or Soft	Suitable Explosive
Tank	X		H	HE
Reinforced Bldg.	X		H	HE
APC	X		H/S	HE
SP Howitzer	X		H/S	HE
Bridge		X	H/S	HE/FAE
Missile	X	X	S	FAE
Aircraft	X	X	S	FAE
Troops	X	X	S	FAE
Antennae		X	S	FAE
Motor Vehicles	X	X	S	FAE
Unreinforced Buildings	X	X	S	FAE

HE = High Explosive
FAE = Fuel-Air Explosive

Table IV: Hard and soft targets, blast couplings, and blast sources.

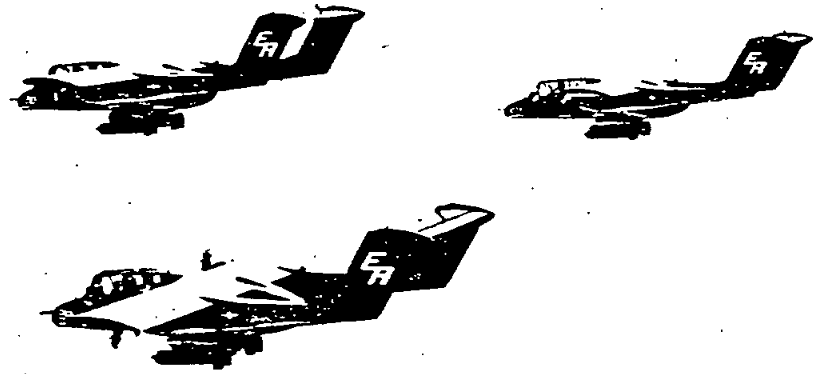
are often looked upon as more haqardous than solids because of potential leakage problems. Geling the liquid is one potential method of dealing with this difficulty that is currently being investigated.

The weaponisation of FAEs is also sometimes controlled by the selection of the delivery container. If the container is already determined, for example, the weapon must be contained in a standard 226 kg (500 pound) bomb assembly, or in a 155mm artillery shell, then the quantity of fuel may be either weight or volume limited. Such constraints can give added importance to high-density fuels.

The only US FAE weapon ever fielded in battle in significant numbers was the BLU-73/B containing 33 kg (72 pounds) of ethylene oxide. It was used by the navy in Vietnam in the CBU-55/B cluster bomb. The CATFAE minefield clearing system is currently in development, but it is still several years from production. Other FAE weapons have been developed with varying success, but none have been deployed. These include the FAESHED, MADFAE, SLUFAE, HFS-I, HFS-II, BLU-95/B, and BLU-96/B. Elsewhere in the West there seems to be little interest in developing FAE weapons with no non-US programmes known to the author, except for the Canadian FALLON FAE line charge mine-clearing system. Persistent reports of Soviet FAE weapons development and use appear to be conjecture based on hearsay or anecdotal evidence, or extrapolations from normal Soviet activities in chemistry and explosive dynamics.

Table V: Safety issues for some FAE fuels.

[illegible]	Corrosive	Inflammable	Explosive	Toxic
[illegible]	No	[illegible]	[illegible]	No
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



OV-10A BRONCO, carrying three CBU-55/B FAE cluster bombs.

The FAE "gap" sometimes alluded to is probably more a worse case fear than a hard reality. In any event, the designation of Soviet or Westen FAE weapons as "second generation" or "third generation" considerably inflates the hard reality which better suggests the existence of a "1-1/2" generation at best.

Deployment and Use

FAE weapons development has been somewnat erratic over the years. Some of this has originated from misunderstandings of the FAE phenomena, some from the difficult weaponisation problem which to some degree remains yet unsolved, and some to the West's fixation on Soviet tanks, the hardest of hard targets. FAE, of course, is not well matched against hard targets. On the other hand, there is now sufficient knowledge and experience to successfully get on with the weaponisation. As for Soviet tanks, the tactician would surely acknowledge that there are additional targets on the battlefield of comparabe importance that are ideal soft targets for FAE. For example, the loss of battalion C^3I assets could effect the battle as much as the loss of all the unit's tanks. Moreover, the global political picture is slowly changing. A study done by the International Institute for Strategic Studies has suggested that future combat is much more likely to occur where hard, armoured targets will be infrequent, but where soft targets will be the rule.

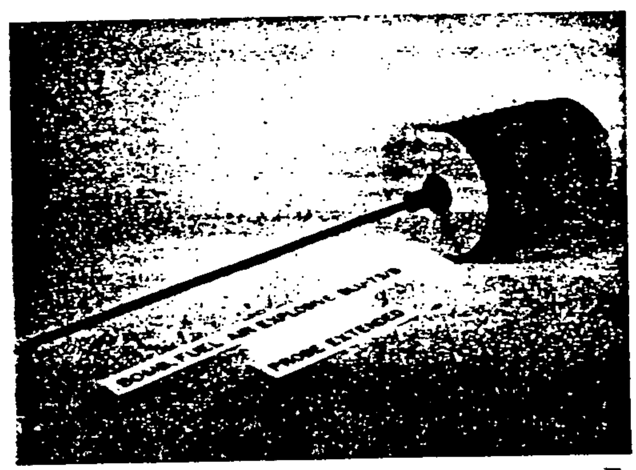
FAE weapons are sufficiently novel that the implications of their existence should be examined. FAE fuel clouds envelop targeted areas. Accordingly, the FAE projectile need not make a direct hit on the target to be effective. For example, a riveted aircraft would be unharmed if a 227 kg HE bomb exploded five metres away on the other side of the revetment. A 227 kg FAE weapon set off at the same distance would create a ten-metre radius aerosol cloud enveloping part of the revetment and the enclosed aircraft which would be severely damaged by the detonation. This means that the CEP and guidance requirements for FAE delivery systems could be considerably eased. The cost consequences of such reduced requirements could be significant.

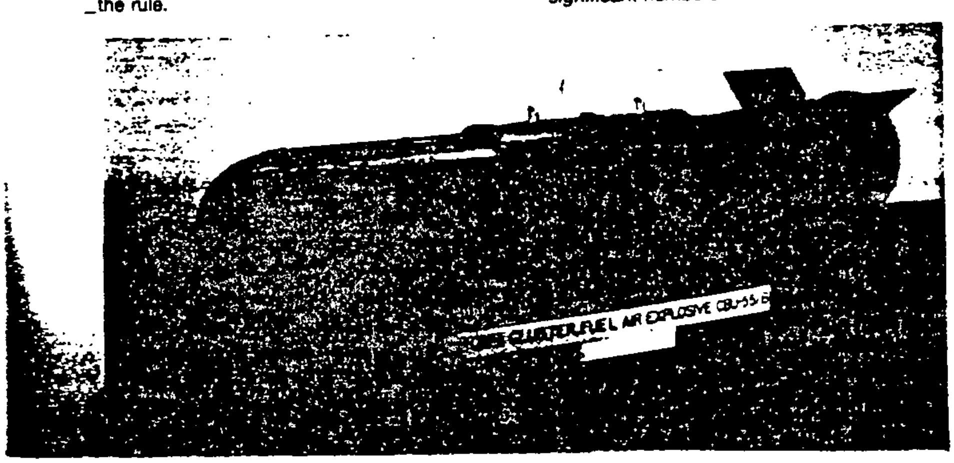
CATFAE, a mobile minefield clearing system with 21 catapult-launched rounds, each containing 63 kg (139 pounds) of FAE fuel, will penetrate conventional minefields with such ease and speed that it brings into question all future tactics that rely on conventional mine barriers. Moreover, the CATFAE rounds would be highly effective against dismounted infantry in dug-in squad and platoon positions. Foxholes and buildings provide very little protection against an enveloping FAE cloud and its blast effects. A single round could have a lethal radius of ten metres or more.

FAE as a demolition mine-clearing weapon was used in Vietnam to prepare helicopter landing sites in the jungle by clearing foliage and mines. FAE weapons used in this manner give additional flexibility to helicopter operations.

This form of explosive could become the most frequent weapon of choice in future conflicts, because it is primarily a soft-target weapons. Recent history suggests that the era of big power wars may have ended. While nuclear powers dare not attack each other, smaller nations continue manoeuvring for advantage

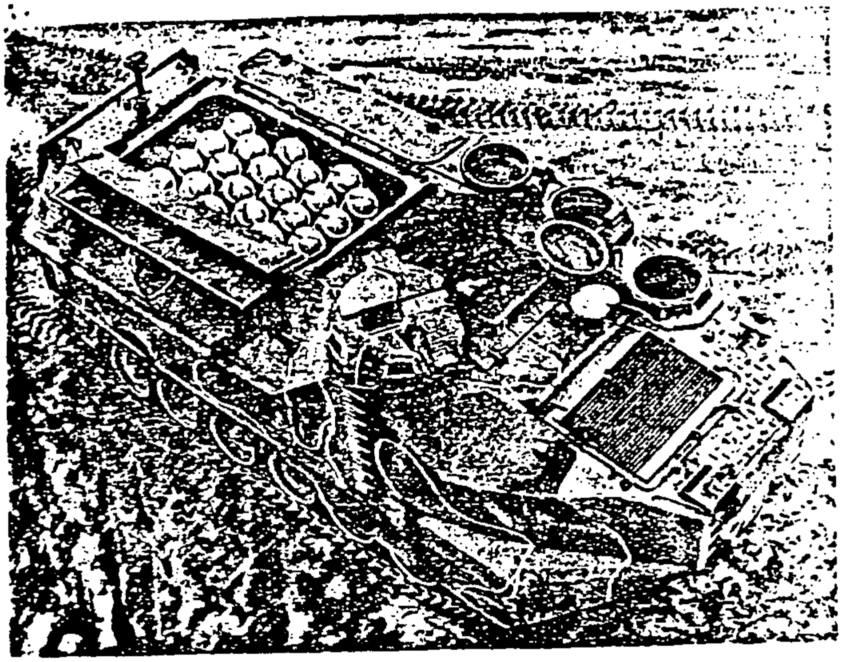
The BLU-73/B FAE bomblet (right) contains 33kg of ethylene oxide. Three BLU-73/Bs are accommodated inside the CBU-55/B cluster bomb (below), the only FAE weapon ever used in battle in significant numbers.





vis-a-vis their neighbours and the larger powers. Conflict in such a context is more likely to present soft rather than hard targets. It is important to understand, however, that the essential area weapon characteristic of FAE gives one relativley little capacity to discriminate between targets and, therefore, precludes its efficacy in operations directly among civil populations.

The future of FAE and its weaponisation will depend very much on its assessed utility as a total system within the combat requirements of the West. It has potential in the classical combat context or any combat where there are identifiable soft targets. The most productive future developmental efforts will probably be in the direction of weaponisation and the creation of self-detonating



The latest operational application of FAE is the CATFAE (Catapult-Launched FAE) mine-clearing system, currently under development for the USMC.

Louis Lavoie

Fuel-Air Explosives, Weapons, and Effects

A fuel-air explosive (FAE) is, by definition, a detonable material that gets most, or all, of its required oxygen from the air. Two almost unique properties of FAE are that it carries little or no oxygen with it, thereby giving it good weight efficiency, and that the detonation occurs over a significant area thereby generating a greater impulse than with a point detonation characteristic of conventional high explosives. Exceptions to the latter point, that will not be discussed in detail here, are dispersed, conventional high explosive powders, and nuclear explosives.

Reports of Soviet use of FAE in Afghanistan have revived interest in FAE weapons by the US military after several years of relative neglect. The zenith of US development may have been reached in January 1973 with the detonation of an FAE device next to the decommissioned destroyer escort, USS MCNULTY, which eventually caused it to sink. However, at least 13 years earlier work was in progress at the China Lake Naval Weapons Center which, by the late 1960s, led to operational tests in Vietnam and the design of the CBU-55/B containing 3, BLU-73/B FAE bombs. Since the late 1970s interest in FAE weapons has declined except for the CATFAE minefield clearing system and the stillborn SLUFAE, also intended for mine clearing. What are fuel-air explosives, how do they work, and why have they alternately excited and disappointed the military community? In this article we will try to answer these questions as well as address the issues of weaponisation, and tactical application

Mr. Lavoie is a defence analyst for the Defense Systems Group of Honeywell Inc., in Minnesota.

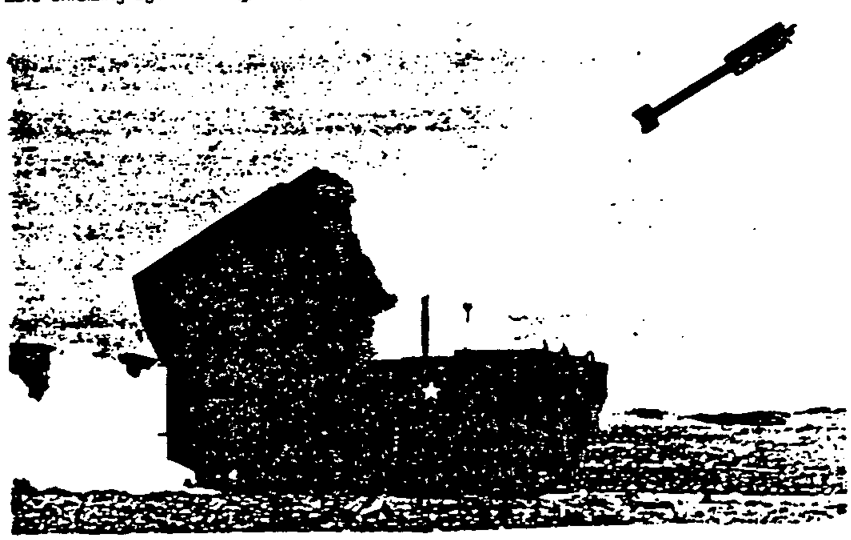
Technical Background

Precisely as the name implies, fuel-air explosives are explosives that rely on oxygen in the air as the primary source of the indispensable oxidizing agent. Several early references in the literature otherwise, are incorrect. For example, FAE detonation in space is a contradiction in terms. Other early references to FAE "burning" in an oxygen-free environment are beside the point, since "burning" and "detonation" are not the same thing. Burning is "slow" oxidation (rusting iron is even slower yet) while detonation is very quick, propagating through the reacting medium at velocities of several kilometres per second.* The fuel-air explosion process contrasts to that of conventional high explosives, such as TNT, which carry adequate oxygen already attached to the explosive molecule (Figure 1). It should be noted, however, that the energy output of conventional high explosives can be boosted by adding oxidizer if their molecules are naturally oxygen lean (TNT), or by adding a reducing agent such as aluminum, if fuel lean (ammonium nitrate). In some cases the additional oxidizer can come from the air just as with FAE. Indeed, some of these explosives, when dispersed as powders, are coming to be grouped with FAE and other high impulse explosives under the name of enhanced blast munitions (EBM).

Fuel-air explosives are more weight efficient than conventional explosives since they obtain their oxygen from the air. Figure 1 shows that 42 % of the weight of TNT is due to the oxygen it must carry with it while 41 and 47 % of the weight of the consumables (fuel and oxygen) in, respectively, propylene oxide/air or aluminum dust/air explosions, comes from the

** Some FAE fuels, for example ethylene and propylene oxides, have an oxygen atom in the molecule and, indeed, can exothermally decompose in the absence of air, but they don't detonate. Also contrary to some references in the defence literature, many FAE fuels are relatively benign e.g. kerosene.*

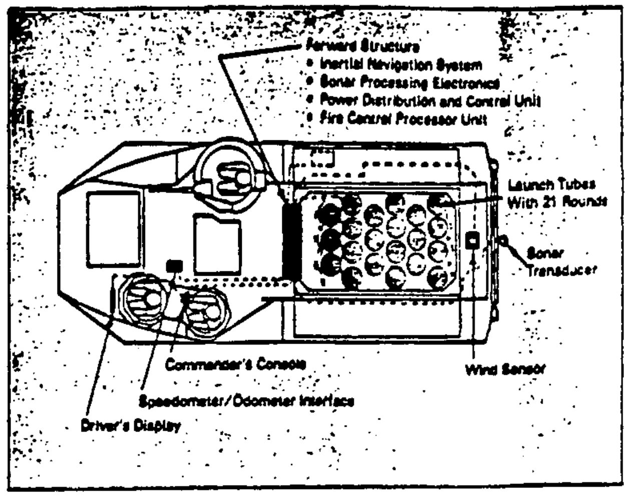
SLUFAE was an earlier US attempt at FAE for mine-clearing purposes.



air and is not carried with the explosives. Accordingly, weight for weight propylene oxide and aluminum release 7.9 and 7.4 times as much energy as TNT (Table I).

There are many possible FAE fuels, but practical onsiderations such as safety quickly reduce the list. The unclassified list of known detonable FAE fuels is not very large. Hydrocarbons are the most numerous. Table II lists some of those that have been demonstrated to detonate as well as including non-hydrocarbon fuels. Indeed, hydrocarbons attracted early civil attention to the FAE phenomenon because of accidents in the petroleum industry.

Arrangement of a CATFAE vehicle (AAVP-7A1 hull).



Below: Fig. 1: Idealised chemical reactions of exploding TNT and FAE fuels.

100 kg TNT:

$$12\,C_6H_2CH_3(NO_2)_3 \rightarrow 14\,CO_2 + 24\,CO + 46\,C + 17\,N_2 + 20\,H_2O + 7\,H_2 + 2\,NH_3$$

42 kg O_2

100 kg Propylene Oxide:

$$C_3H_6O + 4\,O_2 \rightarrow 3\,CO_2 + 3\,H_2O$$

69 kg from the air

100 kg Decene:

$$2\,C_{10}H_{22} + 30_2 \rightarrow 20\,CO_2 + 22\,H_2O$$

34 kg from the air

100 kg Aluminum Powder:

$$4\,Al + 30_2 \rightarrow 2\,Al_2O_3$$

89 kg from the air

Fuel	kcal/g	kcal/cm³
Decane	11.3	8.5
Kerosene	10.2	8.2
Propylene Oxide	7.9	6.6
Aluminum (powder)	7.4	11*
Ethylene Oxide	6.9	6.0
TNT	1.1	1.6

* Although elemental aluminum has a density of 2.7 the bulk powder densities are significantly less typically in the range of 0.6 to 1.5 g/cm³.

Table I: Specific energy of some FAE fuels.

No theory of detonation exists that can predict the detonability of a potential FAE material. Many fuels will burn (deflagrate) without detonating. Others will only detonate if suitably excited by a powerful enough source, and some will detonate quite easily. The critical detonation energy depends on the type of fuel, the fuel particle or drop size if it is solid or liquid, the energy deposition rate (power), the fuel-air ratio, and, to a lesser extent, the temperature and humidity. A useful rule of thumb is that an FAE detonator should contain a conventional explosive mass about 1 % of the FAE mass.

FAE as Weapons

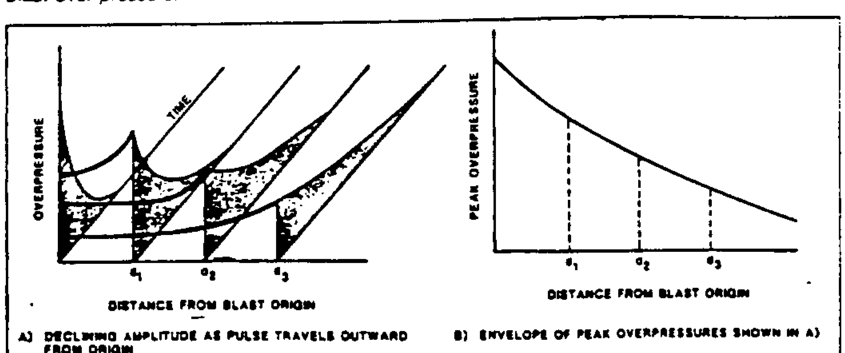
The weaponisation of fuel-air explosives would be greatly simplified if a good way could be found to cause the fuel to self detonate at the right moment. Thus far research in this area has been only slightly successful with fairly impractical results achieved by injection of highly reactive fluorine or bromine trifloride into the fuel cloud causing detonation. Some progress is also being made with autodetonating gelled fuels.

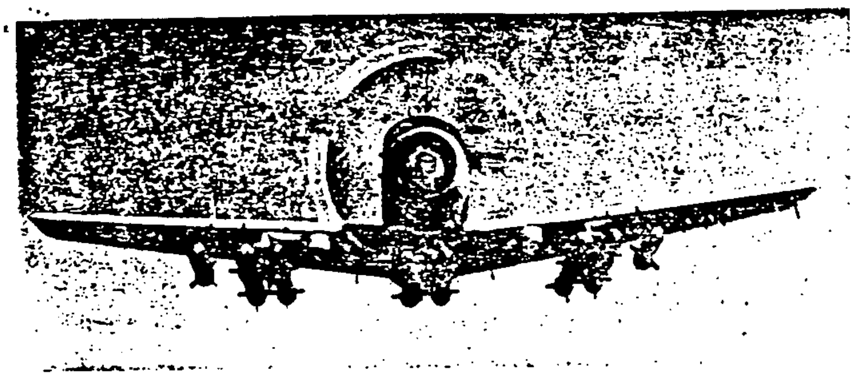
Apart from nuclear weapons, pure blast weapons are believed by some in the defence community to be relatively ineffective unless augmented with penetrators, fragmentation, incendiary, or other damage-producing agents. Nevertheless, FAEs are effective precisely because of their blast. To understand this apparent contradiction it is necessary to use more exact terms than "blast" and to relate these new terms to target vulnerability.

The blast produced by any explosive can be charactensed by peak overpressure and impulse* at a given distance from the centre of the detonation. Overpressure is the pressure increase above normal ambient caused by the heated and expanding products of the explosive chemical reaction. At a point some distance from the blast origin the passing blast wave will cause the pressure to abruptly increase from ambient to some peak value, then decay relatively slowly back to ambient. The greater the distance from the origin of the blast, the less the peak overpressure of the passing wave (Figure 2). Impulse at these same measurement points is the product of the overpressure and the duration of its application. If the overpressure occurred as a square wave, the impulse would be calculated as just overpressure times its duration. But overpressure decays exponentially, so its waveform appears more triangular than square. Accordingly, an exact expression for impulse requires the time integration of overpressure (I = ? P dt.) However, in some cases it is adequate to assume the overpressure pulse is shaped like a right triangle and compute the impulse as the area of the triangle (I = 0.5 Pt)

* *The term "impulse," is used here as it is generally used in the blast and vulnerability literature, which is strictly speaking, impulse per unit area. Of course, true impulse is the time integral of force.*

Fig. 2: Pulse shape in space and time of blast over pressure.





Above: This Vietnam-era photo depicts a SKYRAIDER carrying 14 CBU-55/B FAE bombs.

where "t" is the decay time constant. There are several factors that establish the duration of the overpressure pulse, and hence the impulse, including the quantity, energetics, spatial distribution of the exploding material, and the distance from the centre of the explosion. Useful approximations for computing FAE overpressure and impulse are given in Table III.

Blast waves load targets through diffraction and drag coupling. Targets are damaged in diffraction loading because of the pressure differences that appear across them as the blast wave passes. The coupling is optimum when the blast wave duration is less than one fourth the natural vibration period of the target. Lightweight targets have short periods. This implies short, high-pressure blasts are needed to damage them, since the period is proportional to the square root of the target mass. Accordingly, diffraction-dominated coupling is most effective against overpressure sensitive targets

Acetylene
Aluminum
Butane
Decane
Ethane
Ethylene
Ethylene Oxide
Heptane
Kerosene
Methane
Propane
Propylene
Propylene Oxide

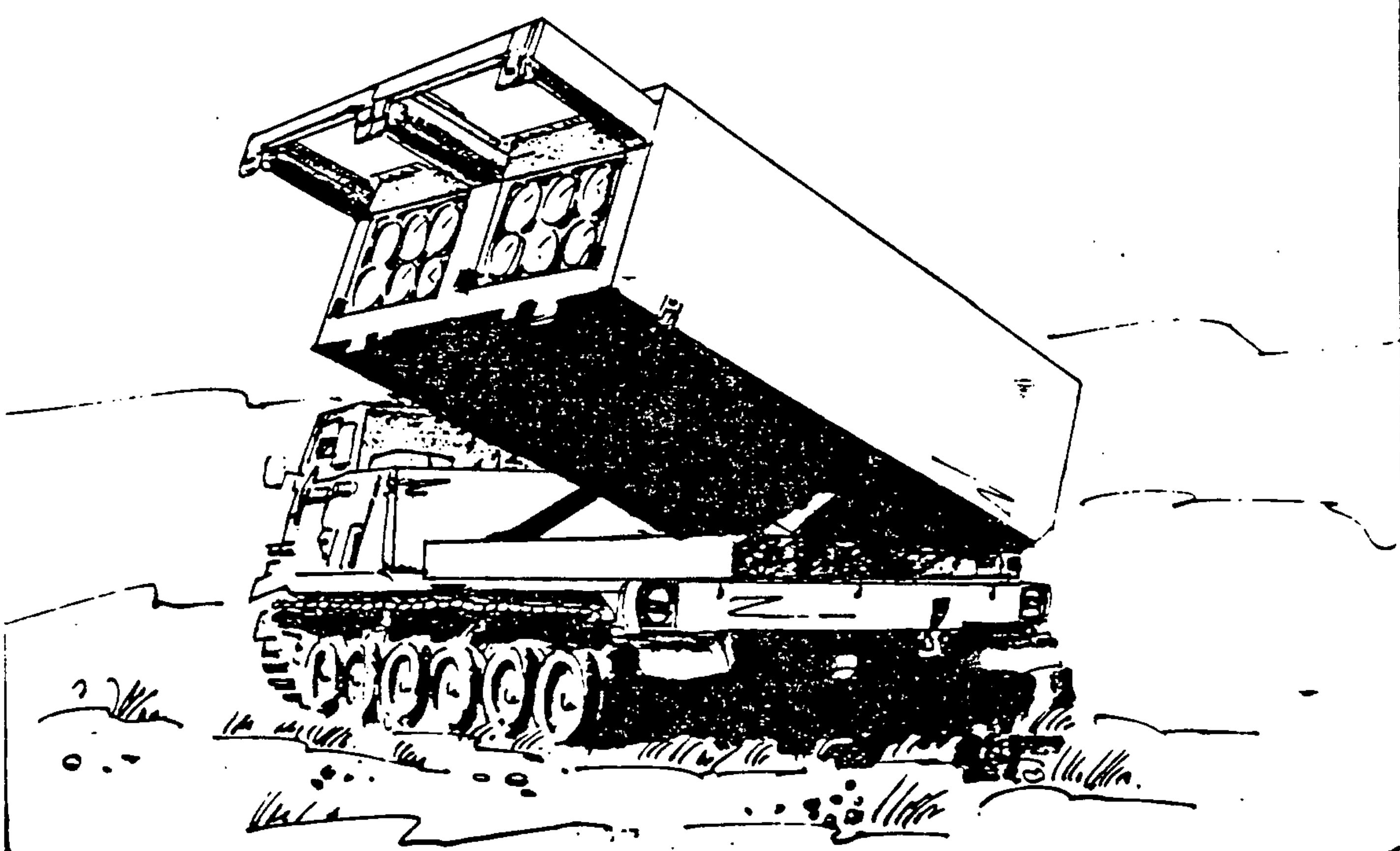
Table II: Some possible FAE fuels that have been successfully detonated.

Targets are damaged by drag loading because of the drag resistance to the air moving rapidly over them. Drag load damage increases in proportion to the duration of the blast. Since impulse is the product of overpressure and time, it is clear that impulse dominated blast loading is most effective against drag-sensitive targets. Drag-sensitive targets are usually considered "soft," while diffraction-sensitive targets are usually considered "hard" (Table IV).

Many targets are vulnerable to both diffraction and drag loads. For example, an automobile exposed to a blast with its windows closed might have its roof crushed and windows broken by diffraction loads, while its radio antenna is torn off and the vehicle rolled over by drag loads.

FAE weapons, with their relatively long impulse and relatively low blast overpressure, are ideally best matched to soft targets. Aircraft, unreinforced buildings, missiles of all kinds, trucks and other unarmoured motor vehicles, radar and communications antennas, and troops are soft. Lightly armoured combat vehicles, APCs and the like, reinforced buildings, concrete bunkers, artillery, and tanks vary from intermediate to hard, and accordingly may not be suitable FAE targets. However, one should not overlook the possibility of attacking the soft sub-systems mounted on hard targets. For example, tanks and APCs could be rendered virtually useless by destroying their antennas and external stores.

Any target, hard or soft, requires a certain minimum or critical impulse and peak over-



pressure to be damaged. Once having satisfied these minimum requirements any combination of impulse and overpressure will do the job. This information can be very conveniently presented in a P/I vulnerability diagram, as shown in Figure 3a. The curve in Figure 3a separates the vulnerable and invulnerable P/I domains for a given target. Every target has its own curve. The harder the target, the more the curve moves up and to the right, reflecting

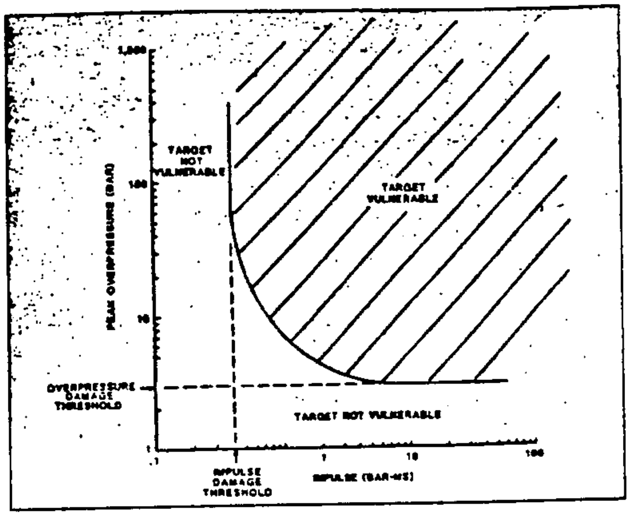


Fig. 3a: Target pressure/impulse vulnerabilivy.

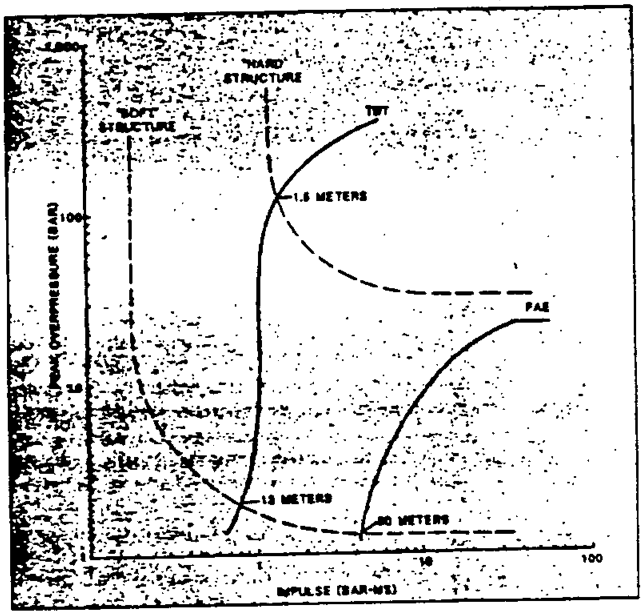


Fig. 3b: Companson of hard and soft target vulnerability to 227kg of TNT and FAE.

greater minimum impulse and overpressure for assured destruction. It is often not practicable to calculate the curve, even with a large computer, although it can be computed for some simple systems. The curve is more frequently defined by a combination of expenmental and computational techniques.

Figure 3a represents a hypothetical soft structure vulnerability. Figure 3b shows the P/I curves for hypothetical soft and hard structures together with a plot of P and I as a function of blast radius for 227 kilograms of TNT and 227 kilograms of a typical FAE fuel. Figure 3b instantly shows the advantages and limi-

tations of FAE over conventional high explosives. FAE will not destroy the hard structure since the FAE curve and hard structure curve do not intersect. Moreover, increasing the amount of FAE fuel will not help since that merely extends the FAE curve to the right (peak overpressure for an FAE fuel is independent of the quantity of fuel). On the other hand, the FAE and soft structure curves inersect at 30 metres on the FAE curve. This is the lethal radius for this FAE weapon. Compare this to the 12-metre intersection point on the TNT curve. Clearly the lethal radius against this soft structure for 227 kilograms of FAE exceeds that of an equal quantity of TNT by two and a half times.

Table III: FAE blast computation.

Approximate incident peak overpressure (P, psi) and impulse (I, psi - ms) at radius (R, ft) for detonation of organic FAE fuel of weight (w, pounds) with aerosol cloud touching ground and 5 to 1 diameter to height ratio. Results useful to 2R. (Simple [illegible] from empirical equations by Larry Josephson of China Lake Naval Weapons Center)

$Z = R/W^{1/3}$

$P = 915$ [illegible] for $Z < 4.5$

$P = 20{,}000\, e^{-Z} + 150\, e^{-0.17Z}$ for $Z \geq 4.5$

$I = 0.18\, PW^{1/3}(2 - 0.2\, e^{-0.31Z})$ for $Z < 4.5$

$I = 0.14\, PW^{1/3}\left(e^{-0.006Z^2} + 2 \ln \frac{Z}{3.7}\right)$ for $Z \geq 4.5$

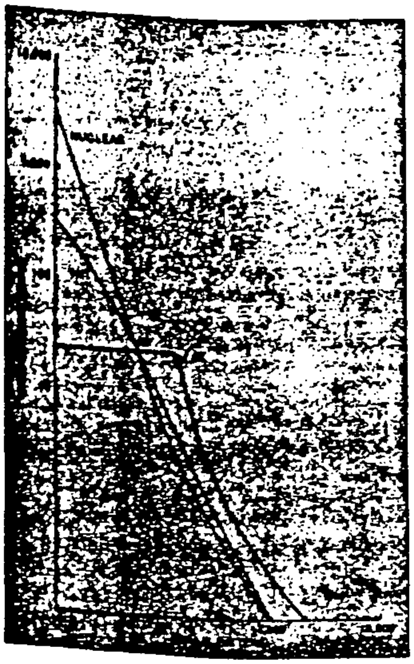


Fig. 4a: Overpressure for 1KT nuclear, TNT, FAE.

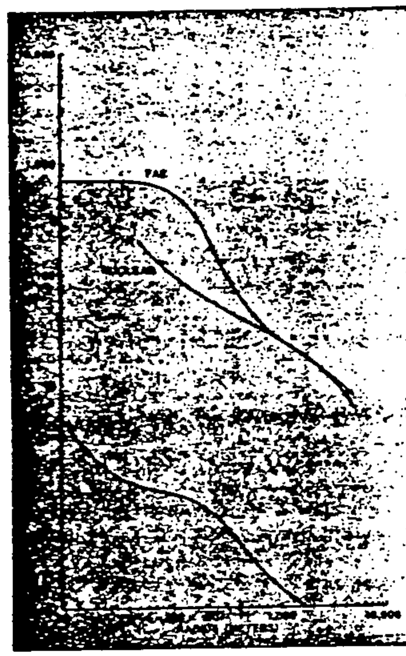


Fig. 4b: Impulse for 1KT nuclear, TNT, FAE.

A comparison of overpressure and impulse versus distance for equivalent/equal masses of nuclear, TNT, and FAE explosives immediately reveals the advantages and limitations of FAE weapons (Figure 4a, b). The peak overpressures available in the near field from FAE are substantially less than those of TNT and nuclear weapons. This significantly limits the effectiveness of FAE against hard targets. On the other hand, Figure 4b shows that the FAE impulse is about a hundred times greater than TNT. This gives FAE a much greater effectiveness against soft targets. It is also appropriate here to point out that FAE is not a substitute for nuclear weapons as has sometimes been reported in the literature. It might be used on a small scale to simulate nuclear weapons effects for vulnerability testing, but the quantity of FAE fuel needed to substitute for a tactical nuclear weapon of even fractional kiloton yield does not suggest a very practical device. An FAE weapon with a yield equivalent to a 0.1 kiloton nuclear weapon would weigh 45,000 kilograms and have a volume of 52 cubic metres.

The weaponisation of FAE is dominated by the challenges of creating the proper fuel air mixture and then detonating it at the correct time. A generic FAE bomb (Figure 5) might be a right circular cylinder, two or three diameters long, filled with fuel and fuzed to burst open at a suitable distance above the ground. A burster charge of high explosive, weighing 1 or 2% of the fuel weight, is located in a tube along the bomb's central axis. The purpose of the burster charge is to break open the container and distribute the fuel in a cloud such that the volume of air filled will contain sufficient oxygen for complete fuel oxidization. This volume is determined by the quantity and reaction chemistry of fuel (Figure 1). When the fuel is a liquid the burster charge also serves the purpose of shattering the liquid into a micro-mist aerosol so that it can be detonated. This is an extremely important and delicate function since the detonability of the fuel is determined, in part, by the aerosol droplet size.

The aerosol is detonated once the cloud reaches the diameter for the optimum fuel-air ratio (also kown as the stoichiometric ratio). The "second event" detonator, like the burster charge, is also a high explosive weighing a few percent of the fuel weight. The reason the burster charge doesn't detonate the fuel while the detonator does, is that the fuel is not in a detonable aerosol form at the "first event." The detonator is ejected from the generic bomb shortly before the burster charge goes off. It is slowed with a suitable drag device so that it enters the aerosol cloud and detonates at the instant of fuel-air stoichiometry. An FAE weapon would be considerably more simple if this obviously very tricky procedure could be avoided by finding some way to get the fuel to self detonate the instant it reaches stoichiometry.

The effects of weather on FAE cloud formation and detonation are not very well known. Apart from some anecdotal data it has been established that temperature and humidity can change the required detonation energy by as much as 10 or 20 %.

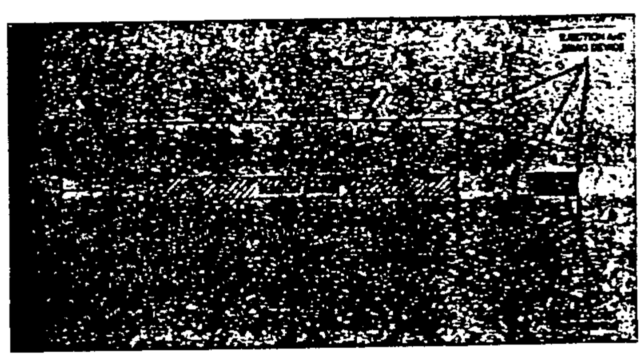


Fig. 5: Generic FAE bomb.

Safety is an important issue in weaponising FAE. Some fuels, such as aluminum powder, are benign, while others may be corrosive, unstable, inflammable, explosive, or toxic. Table V lists a few of these factors for some selected fuels. Sometimes a fuel can be selected to reduce some of these hazards. For example, the high volatility of ethylene oxide makes it difficult to contain safely at elevated temperatures. Propylene oxide is, nevertheless, a somewhat difficult material to handle and store, and could pose a fire hazard if the container leaked. Indeed, liquid fuels, in general,

System	Loading		Hard or Soft	Suitable Explosive
	Diffraction	Drag		
Tank	X		H	HE
Reinforced Bldg.	X		H	HE
APC	X		H/S	HE
SP Howitzer	X		H/S	HE
Bridge		X	H/S	HE/FAE
Missile	X	X	S	FAE
Aircraft	X	X	S	FAE
Troops	X	X	S	FAE
Antennae		X	S	FAE
Motor Vehicles	X	X	S	FAE
Unreinforced Buildings	X	X	S	FAE

HE = High Explosive
FAE = Fuel-Air Explosive

Table IV: Hard and soft targets, blast couplings, and blast sources.

are often looked upon as more haqardous than solids because of potential leakage problems. Geling the liquid is one potential method of dealing with this difficulty that is currently being investigated.

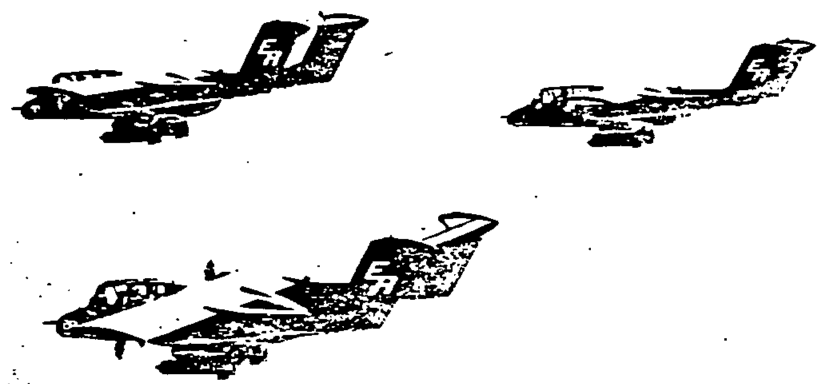
The weaponisation of FAEs is also sometimes controlled by the selection of the delivery container. If the container is already determined, for example, the weapon must be contained in a standard 226 kg (500 pound) bomb assembly, or in a 155mm artillery shell, then the quantity of fuel may be either weight or volume limited. Such constraints can give added importance to high-density fuels.

The only US FAE weapon ever fielded in battle in significant numbers was the BLU-73/B containing 33 kg (72 pounds) of ethylene oxide. It was used by the navy in Vietnam in the CBU-55/B cluster bomb. The CATFAE minefield clearing system is currently in development, but it is still several years from production. Other FAE weapons have been developed with varying success, but none have been deployed. These include the FAESHED, MADFAE, SLUFAE, HFS-I, HFS-II, BLU-95/B, and BLU-96/B. Elsewhere in the West there seems to be little interest in developing FAE weapons with no non-US programmes known to the author, except for the Canadian FALLON FAE line charge mine-clearing system. Persistent reports of Soviet FAE weapons development and use appear to be conjecture based on hearsay or anecdotal evidence, or extrapolations from normal Soviet activities in chemistry and explosive dynamics.

Table V: Safety issues for some FAE fuels.

[illegible]	[illegible]	[illegible]	Explosive	Toxic
[illegible]	[illegible]	[illegible]	[illegible]	No
[illegible]	[illegible]	[illegible]	[illegible]	No
[illegible]	[illegible]	[illegible]	[illegible]	Yes
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

OV-10A BRONCO, carrying three CBU-55/B FAE cluster bombs.



The FAE "gap" sometimes alluded to is probably more a worse case fear than a hard reality. In any event, the designation of Soviet or Westen FAE weapons as "second generation" or "third generation" considerably inflates the hard reality which better suggests the existence of a "1-1/2" generation at best.

Deployment and Use

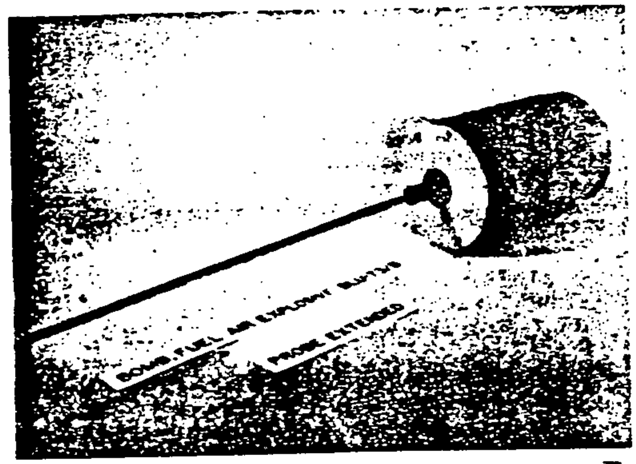
FAE weapons development has been somewhat erratic over the years. Some of this has originated from misunderstandings of the FAE phenomena, some from the difficult weaponisation problem which to some degree remains yet unsolved, and some to the West's fixation on Soviet tanks, the hardest of hard targets. FAE, of course, is not well matched against hard targets. On the other hand, there is now sufficient knowledge and experience to successfully get on with the weaponisation. As for Soviet tanks, the tactician would surely acknowledge that there are additional targets on the battlefield of comparabe importance that are ideal soft targets for FAE. For example, the loss of battalion C^3I assets could effect the battle as much as the loss of all the unit's tanks. Moreover, the global political picture is slowly changing. A study done by the International Institute for Strategic Studies has suggested that future combat is much more likely to occur where hard, armoured targets will be infrequent, but where soft targets will be the rule.

FAE weapons are sufficiently novel that the implications of their existence should be examined. FAE fuel clouds envelop targeted areas. Accordingly, the FAE projectile need not make a direct hit on the target to be effective. For example, a riveted aircraft would be unharmed if a 227 kg HE bomb exploded five metres away on the other side of the revetment. A 227 kg FAE weapon set off at the same distance would create a ten-metre radius aerosol cloud enveloping part of the revetment and the enclosed aircraft which would be severely damaged by the detonation. This means that the CEP and guidance requirements for FAE delivery systems could be considerably eased. The cost consequences of such reduced requirements could be significant.

CATFAE, a mobile minefield clearing system with 21 catapult-launched rounds, each containing 63 kg (139 pounds) of FAE fuel, will penetrate conventional minefields with such ease and speed that it brings into question all future tactics that rely on conventional mine barriers. Moreover, the CATFAE rounds would be highly effective against dismounted infantry in dug-in squad and platoon positions. Foxholes and buildings provide very little protection against an enveloping FAE cloud and its blast effects. A single round could have a lethal radius of ten metres or more.

FAE as a demolition mine-clearing weapon was used in Vietnam to prepare helicopter landing sites in the jungle by clearing foliage and mines. FAE weapons used in this manner give additional flexibility to helicopter operations.

This form of explosive could become the most frequent weapon of choice in future conflicts, because it is primarily a soft-target weapons. Recent history suggests that the era of big power wars may have ended. While nuclear powers dare not attack each other, smaller nations continue manoeuvring for advantage *vis-a-vis* their neighbours and the larger powers. Conflict in such a context is more likely to present soft rather than hard targets. It is important to understand, however, that the essential area weapon characteristic of FAE gives one relativley little capacity to discriminate between targets and, therefore, precludes its efficacy in operations directly among civil populations.



The BLU-73/B FAE bomblet (right) contains 33kg of ethylene oxide. Three BLU-73/Bs are accommodated inside the CBU-55/B cluster bomb (below), the only FAE weapon ever used in battle in significant numbers.

The future of FAE and its weaponisation will depend very much on its assessed utility as a total system within the combat requirements of the West. It has potential in the classical combat context or any combat where there are identifiable soft targets. The most productive future developmental efforts will probably be in the direction of weaponisation and the creation of self-detonating fuels.

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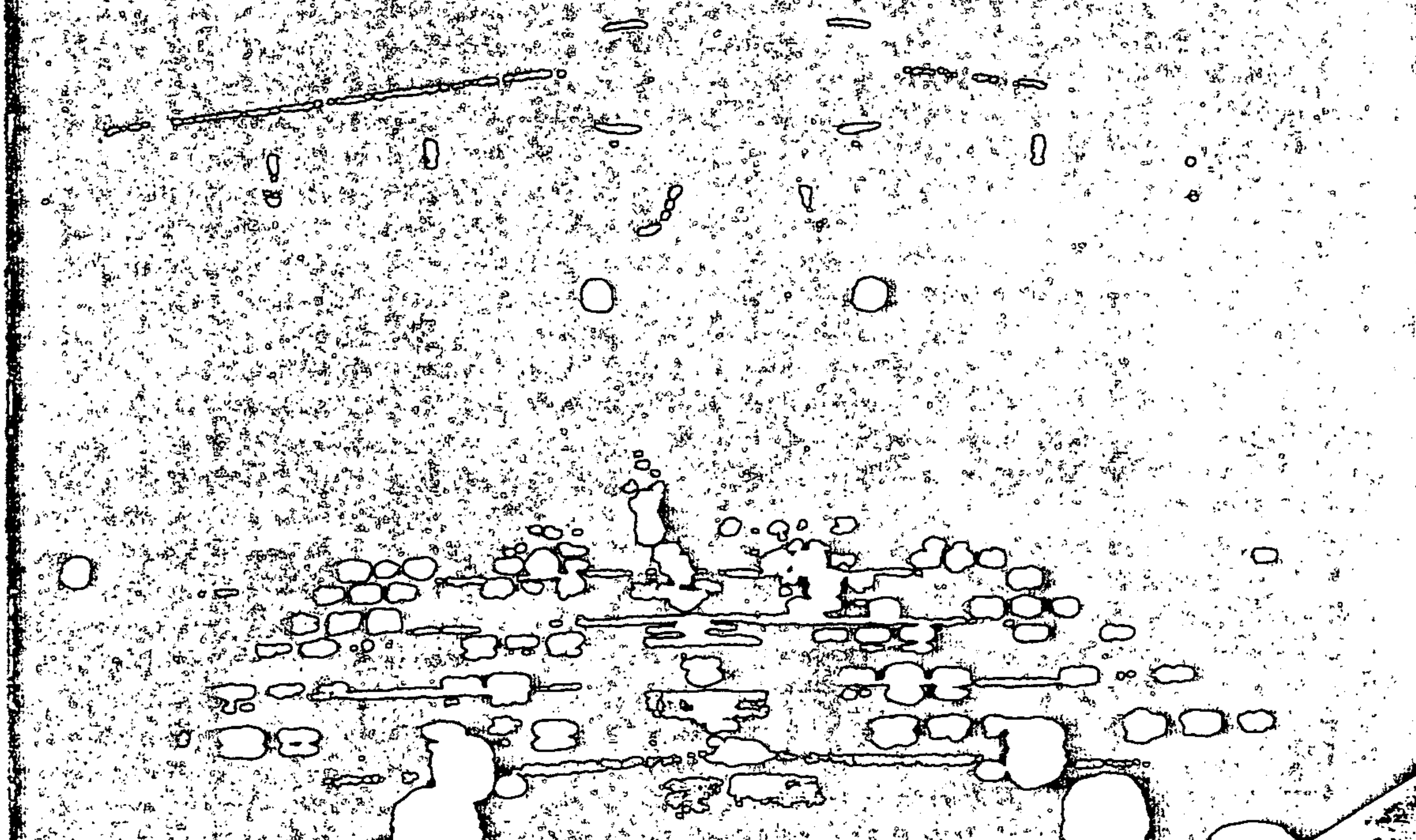

EMBRAER'S 20 Years

MILITARY TECHNOLOGY
No. 9/89 · September 1989

The Italian/Brazilian AMX strike fighter, now about to begin its operational career, figures on our cover on two counts: to accompany the article on the Italian Air Force, starting on p. 50, and to mark EMBRAER's 20th birthday.

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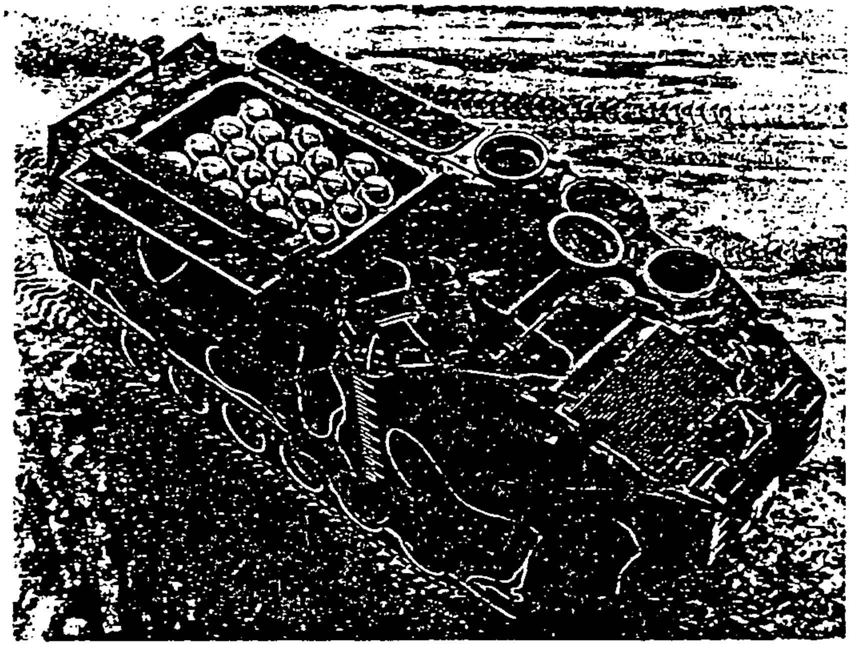


The latest operational application of FAE is the CATFAE (Catapult-Launched FAE) mine-clearing system, currently under development for the USMC.

Louis Lavoie

Fuel-Air Explosives, Weapons, and Effects

A fuel-air explosive (FAE) is, by definition, a detonable material that gets most, or all, of its required oxygen from the air. Two almost unique properties of FAE are that it carries little or no oxygen with it, thereby giving it good weight efficiency, and that the detonation occurs over a significant area thereby generating a greater impulse than with a point detonation characteristic of conventional high explosives. Exceptions to the latter point, that will not be discussed in detail here, are dispersed, conventional high explosive powders, and nuclear explosives.

Reports of Soviet use of FAE in Afghanistan have revived interest in FAE weapons by the US military after several years of relative neglect. The zenith of US development may have been reached in January 1973 with the detonation of an FAE device next to the decommissioned destroyer escort, USS MCNULTY, which eventually caused it to sink. However, at least 13 years earlier work was in progress at the China Lake Naval Weapons Center which, by the late 1960s, led to operational tests in Vietnam and the design of the CBU-55/B containing 3, BLU-73/B FAE bombs. Since the late 1970s interest in FAE weapons has declined except for the CATFAE minefield clearing system and the stillborn SLUFAE, also intended for mine clearing. What are fuel-air explosives, how do they work, and why have they alternately excited and disappointed the military community? In this article we will try to answer these questions as well as address the issues of weaponisation, and tactical application

Mr. Lavoie is a defence analyst for the Defense Systems Group of Honeywell Inc., in Minnesota.

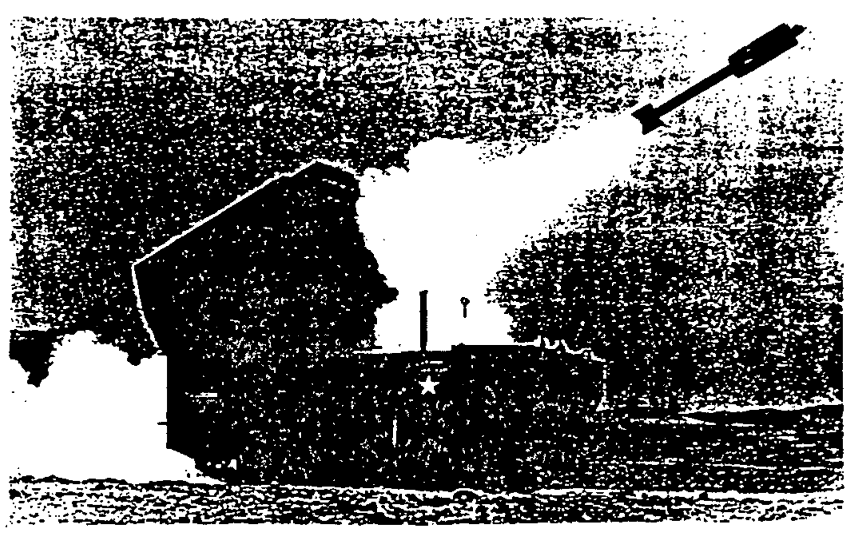
Technical Background

Precisely as the name implies, fuel-air explosives are explosives that rely on oxygen in the air as the primary source of the indispensable oxidizing agent. Several early references in the literature otherwise, are incorrect. For example, FAE detonation in space is a contradiction in terms. Other early references to FAE "burning" in an oxygen-free environment are beside the point, since "burning" and "detonation" are not the same thing. Burning is "slow" oxidation (rusting iron is even slower yet) while detonation is very quick, propagating through the reacting medium at velocities of several kilometres per second.* The fuel-air explosion process contrasts to that of conventional high explosives, such as TNT, which carry adequate oxygen already attached to the explosive molecule (Figure 1). It should be noted, however, that the energy output of conventional high explosives can be boosted by adding oxidizer if their molecules are naturally oxygen lean (TNT), or by adding a reducing agent such as aluminum, if fuel lean (ammonium nitrate). In some cases the additional oxidizer can come from the air just as with FAE. Indeed, some of these explosives, when dispersed as powders, are coming to be grouped with FAE and other high impulse explosives under the name of enhanced blast munitions (EBM).

Fuel-air explosives are more weight efficient than conventional explosives since they obtain their oxygen from the air. Figure 1 shows that 42 % of the weight of TNT is due to the oxygen it must carry with it while 41 and 47 % of the weight of the consumables (fuel and oxygen) in, respectively, propylene oxide/air or aluminum dust/air explosions, comes from the

** Some FAE fuels, for example ethylene and propylene oxides, have an oxygen atom in the molecule and, indeed, can exothermally decompose in the absence of air, but they don't detonate. Also contrary to some references in the defence literature, many FAE fuels are relatively benign e.g. kerosene.*

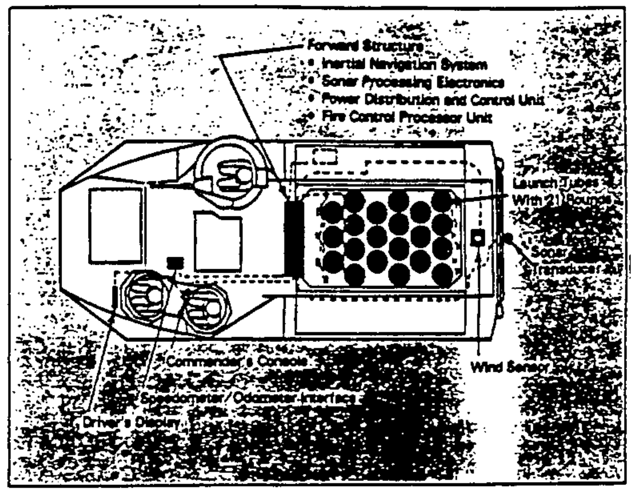
SLUFAE was an earlier US attempt at FAE for mine-clearing purposes.



air and is not carried with the explosives. Accordingly, weight for weight propylene oxide and aluminum release 7.9 and 7.4 times as much energy as TNT (Table I).

There are many possible FAE fuels, but practical onsiderations such as safety quickly reduce the list. The unclassified list of known detonable FAE fuels is not very large. Hydrocarbons are the most numerous. Table II lists some of those that have been demonstrated to detonate as well as including non-hydrocarbon fuels. Indeed, hydrocarbons attracted early civil attention to the FAE phenomenon because of accidents in the petroleum industry.

Arrangement of a CATFAE vehicle (AAVP-7A1 hull).



Below: Fig. 1: Idealised chemical reactions of exploding TNT and FAE fuels.

100 kg TNT:

$$12\, C_6H_2CH_3(NO_2)_3 \rightarrow 14\, CO_2 + 24\, CO + 46\, C + 17\, N_2 + 20\, H_2O + 7\, H_2 + 2\, NH_3$$

42 kg O_2

100 kg Propylene Oxide:

$$C_3H_6O + 4\, O_2 \rightarrow 3\, CO_2 + 3\, H_2O$$

69 kg from the air

100 kg Decane:

$$2\, C_{10}H_{22} + 30_2 \rightarrow 20\, CO_2 + 22\, H_2O$$

34 kg from the air

100 kg Aluminum Powder:

$$4\, Al + 30_2 \rightarrow 2\, Al_2O_3$$

69 kg from the air

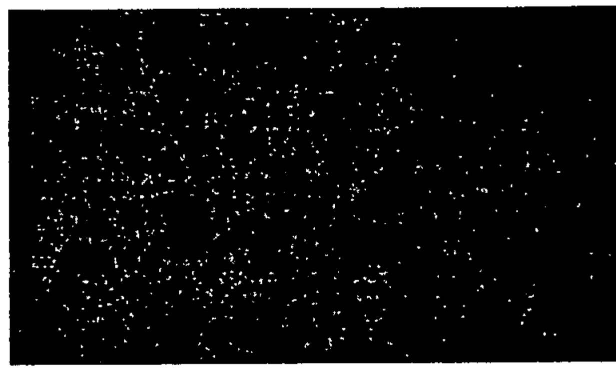


Table I: Specific energy of some FAE fuels.

No theory of detonation exists that can predict the detonability of a potential FAE material. Many fuels will burn (deflagrate) without detonating. Others will only detonate if suitably excited by a powerful enough source, and some will detonate quite easily. The critical detonation energy depends on the type of fuel, the fuel particle or drop size if it is solid or liquid, the energy deposition rate (power), the fuel-air ratio, and, to a lesser extent, the temperature and humidity. A useful rule of thumb is that an FAE detonator should contain a conventional explosive mass about 1 % of the FAE mass.

FAE as Weapons

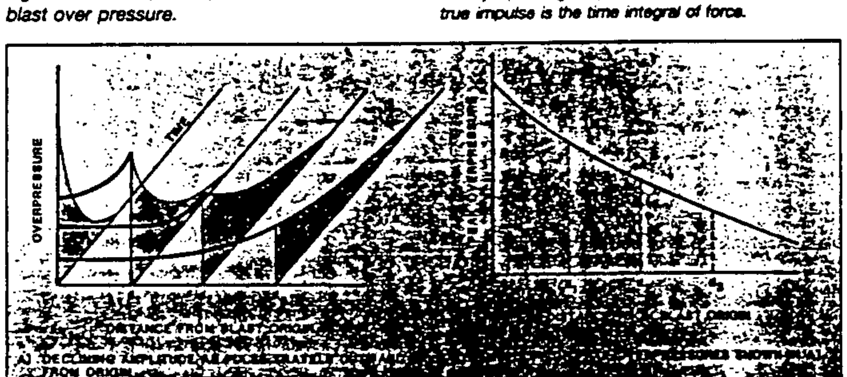
The weaponisation of fuel-air explosives would be greatly simplified if a good way could be found to cause the fuel to self detonate at the right moment. Thus far research in this area has been only slightly successful with fairly impractical results achieved by injection of highly reactive fluorine or bromine trifloride into the fuel cloud causing detonation. Some progress is also being made with autodetonating gelled fuels.

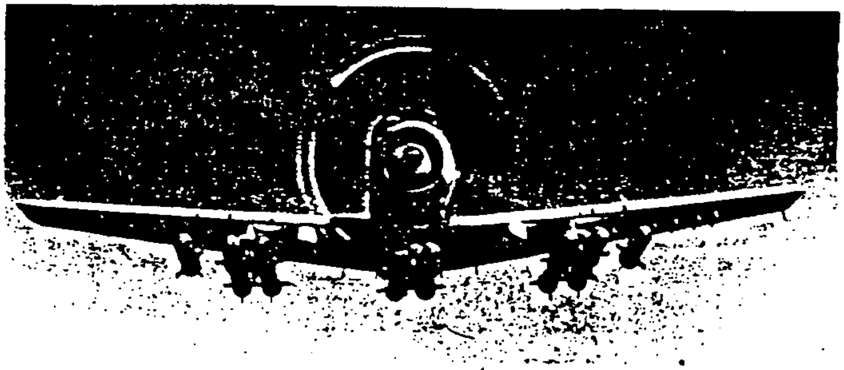
Apart from nuclear weapons, pure blast weapons are believed by some in the defence community to be relatively ineffective unless augmented with penetrators, fragmentation, incendiary, or other damage-producing agents. Nevertheless, FAEs are effective precisely because of their blast. To understand this apparent contradiction it is necessary to use more exact terms than "blast" and to relate these new terms to target vulnerability.

The blast produced by any explosive can be characterised by peak overpressure and impulse* at a given distance from the centre of the detonation. Overpressure is the pressure increase above normal ambient caused by the heated and expanding products of the explosive chemical reaction. At a point some distance from the blast origin the passing blast wave will cause the pressure to abruptly increase from ambient to some peak value, then decay relatively slowly back to ambient. The greater the distance from the origin of the blast, the less the peak overpressure of the passing wave (Figure 2). Impulse at these same measurement points is the product of the overpressure and the duration of its application. If the overpressure occurred as a square wave, the impulse would be calculated as just overpressure times its duration. But overpressure decays exponentially, so its waveform appears more triangular than square. Accordingly, an exact expression for impulse requires the time integration of overpressure (I = ? P dt.) However, in some cases it is adequate to assume the overpressure pulse is shaped like a right triangle and compute the impulse as the area of the triangle (I = 0.5 Pt)

** The term "impulse," is used here as it is generally used in the blast and vulnerability literature, which is strictly speaking, impulse per unit area. Of course, true impulse is the time integral of force.*

Fig. 2: Pulse shape in space and time of blast over pressure.





Above: This Vietnam-era photo depicts a SKYRAIDER carrying 14 CBU-55/B FAE bombs.

where "t" is the decay time constant. There are several factors that establish the duration of the overpressure pulse, and hence the impulse, including the quantity, energetics, spatial distribution of the exploding material, and the distance from the centre of the explosion. Useful approximations for computing FAE overpressure and impulse are given in Table III.

Blast waves load targets through diffraction and drag coupling. Targets are damaged in diffraction loading because of the pressure differences that appear across them as the blast wave passes. The coupling is optimum when the blast wave duration is less than one fourth the natural vibration period ot the target. Lightweight targets have short penods. This implies short, high-pressure blasts are needed to damage them, since the period is proportional to the square root of the target mass. Accordingly, diffraction-dominated coupling is most effective against overpressure sensitive targets

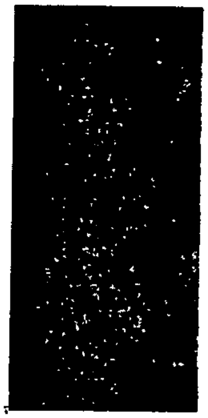


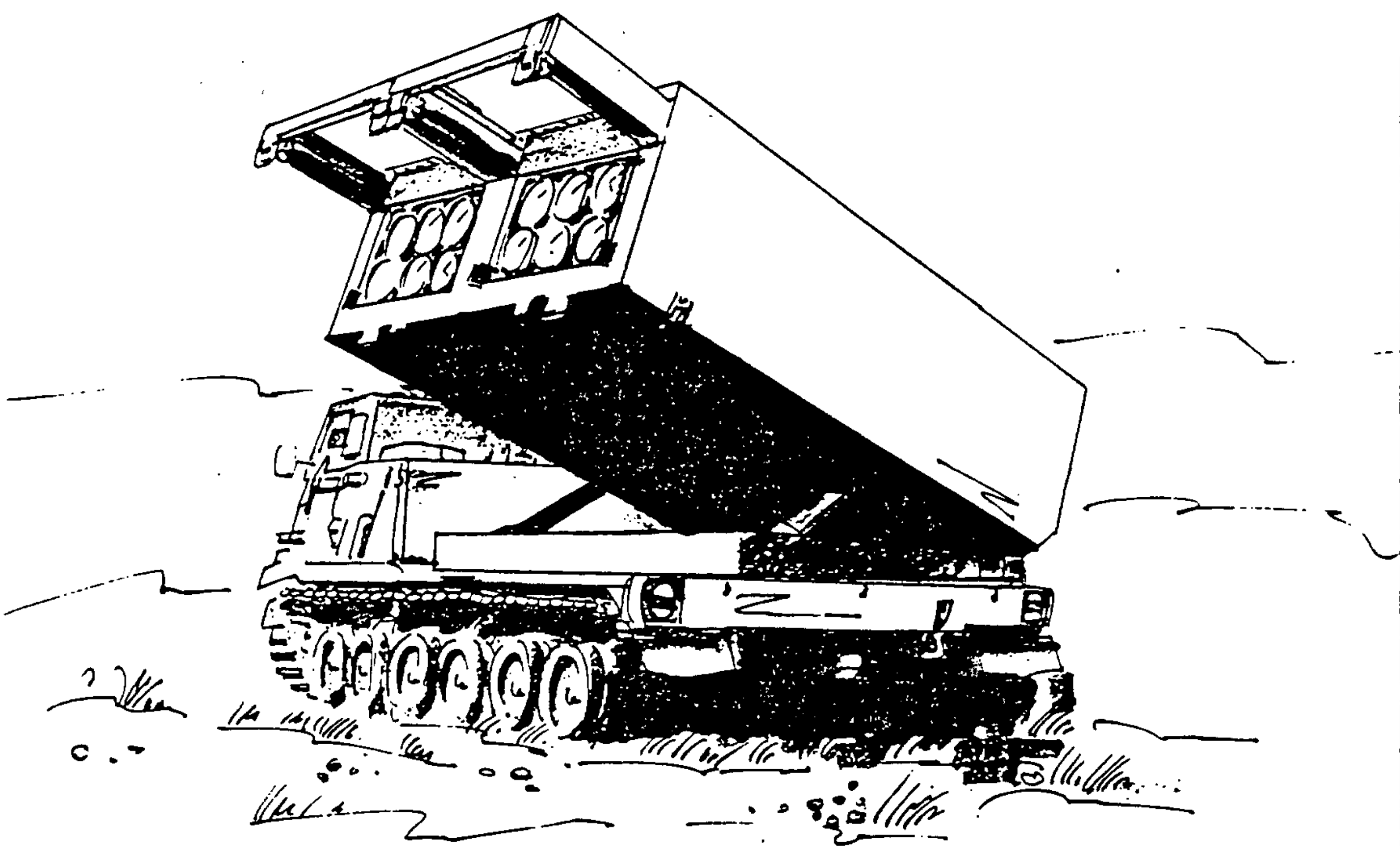
Table II: Some possible FAE fuels that have been successfully detonated.

Targets are damaged by drag loading because of the drag resistance to the air moving rapidly over them. Drag load damage increases in proportion to the duration of the blast. Since impulse is the product of overpressure and time, it is clear that impulse dominated blast loading is most effective against drag-sensitive targets. Drag-sensitive targets are usually considered "soft," while diffraction-sensitive targets are usually considered "hard" (Table IV).

Many targets are vulnerable to both diffraction and drag loads. For example, an automobile exposed to a blast with its windows closed might have its roof crushed and windows broken by diffraction loads, while its radio antenna is torn off and the vehicle rolled over by drag loads.

FAE weapons, with their relatively long impulse and relatively low blast overpressure, are ideally best matched to soft targets. Aircraft, unreinforced buildings, missiles of all kinds, trucks and other unarmoured motor vehicles, radar and communications antennas, and troops are soft. Lightly armoured combat vehicles, APCs and the like, reinforced buildings, concrete bunkers, artillery, and tanks vary from intermediate to hard, and accordingly may not be suitable FAE targets. However, one should not overlook the possibility of attacking the soft sub-systems mounted on hard targets. For example, tanks and APCs could be rendered virtually useless by destroying their antennas and external stores.

Any target, hard or soft, requires a certain minimum or critical impulse and peak over-



...essure to be damaged. Once having satisfied these minimum requirements any combination of impulse and overpressure will do the job. This information can be very conveniently presented in a P/I vulnerability diagram, as shown in Figure 3a. The curve in Figure 3a separates the vulnerable and invulnerable P/I domains for a given target. Every target has its own curve. The harder the target, the more the curve moves up and to the right, reflecting greater minimum impulse and overpressure for assured destruction. It is often not practicable to calculate the curve, even with a large computer, although it can be computed for some simple systems. The curve is more frequently defined by a combination of experimental and computational techniques.

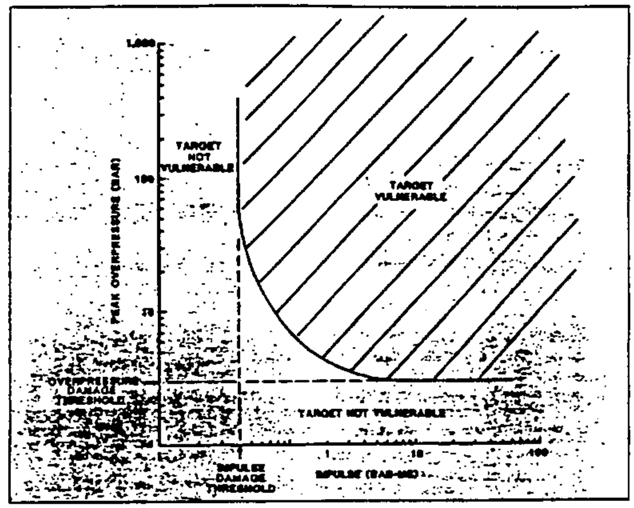


Fig. 3a: Target pressure/impulse vulnerabilivy.

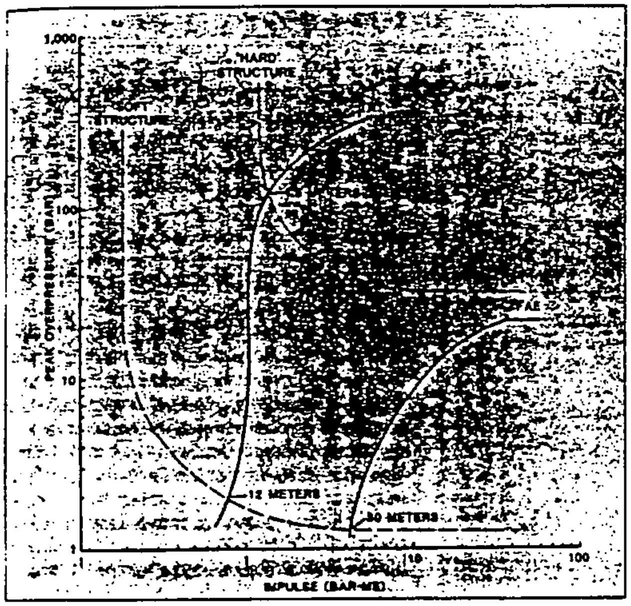
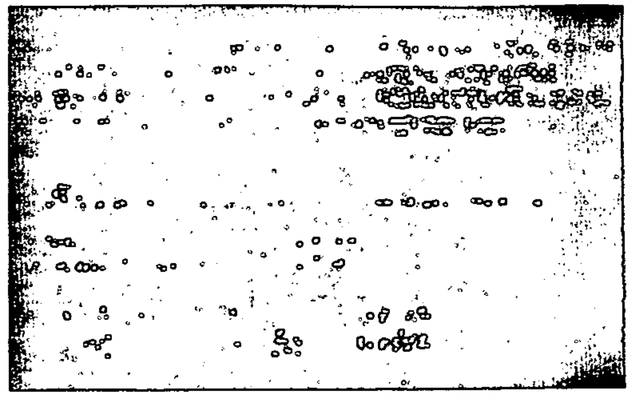


Fig. 3b: Comparison of hard and soft target vulnerability to 227kg of TNT and FAE.

Figure 3a represents a hypothetical soft structure vulnerability. Figure 3b shows the P/I curves for hypothetical soft and hard structures together with a plot of P and I as a function of blast radius for 227 kilograms of TNT and 227 kilograms of a typical FAE fuel. Figure 3b instantly shows the advantages and limi-

tations of FAE over conventional high explosives. FAE will not destroy the hard structure since the FAE curve and hard structure curve do not intersect. Moreover, increasing the amount of FAE fuel will not help since that merely extends the FAE curve to the right (peak overpressure for an FAE fuel is independent of the quantity of fuel). On the other hand, the FAE and soft structure curves inersect at 30 metres on the FAE curve. This is the lethal radius for this FAE weapon. Compare this to the 12-metre intersection point on the TNT curve. Clearly the lethal radius against this soft structure for 227 kilograms of FAE exceeds that of an equal quantity of TNT by two and a half times.

Table III: FAE blast computation.



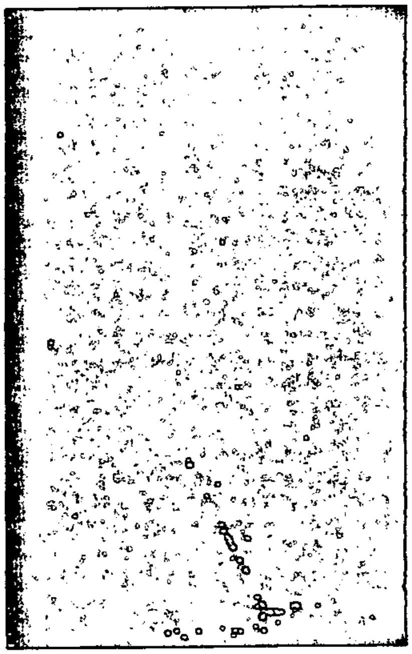


Fig. 4a: Overpressure for 1KT nuclear, TNT, FAE.

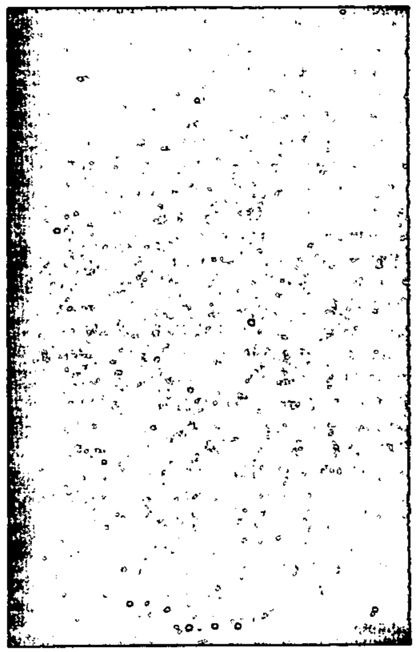


Fig. 4b: Impulse for 1KT nuclear, TNT, FAE.

A comparison of overpressure and impulse versus distance for equivalent/equal masses of nuclear, TNT, and FAE explosives immediately reveals the advantages and limitations of FAE weapons (Figure 4a, b). The peak overpressures available in the near field from FAE are substantially less than those of TNT and nuclear weapons. This significantly limits the effectiveness of FAE against hard targets. On the other hand, Figure 4b shows that the FAE impulse is about a hundred times greater than TNT. This gives FAE a much greater effectiveness against soft targets. It is also appropriate here to point out that FAE is not a substitute for nuclear weapons as has sometimes been reported in the literature. It might be used on a small scale to simulate nuclear weapons effects for vulnerability testing, but the quantity of FAE fuel needed to substitute for a tactical nuclear weapon of even fractional kiloton yield does not suggest a very practical device. An FAE weapon with a yield equivalent to a 0.1 kiloton nuclear weapon would weigh 45,000 kilograms and have a volume of 52 cubic metres.

The weaponisation of FAE is dominated by the challenges of creating the proper fuel air mixture and then detonating it at the correct time. A generic FAE bomb (Figure 5) might be a right circular cylinder, two or three diameters long, filled with fuel and fuzed to burst open at a suitable distance above the ground. A burster charge of high explosive, weighing 1 or 2% of the fuel weight, is located in a tube along the bomb's central axis. The purpose of the burster charge is to break open the container and distribute the fuel in a cloud such that the volume of air filled will contain sufficient oxygen for complete fuel oxidization. This volume is determined by the quantity and reaction chemistry of fuel (Figure 1). When the fuel is a liquid the burster charge also serves the purpose of shattering the liquid into a micromist aerosol so that it can be detonated. This is an extremely important and delicate function since the detonability of the fuel is determined, in part, by the aerosol droplet size.

The aerosol is detonated once the cloud reaches the diameter for the optimum fuel-air ratio (also kown as the stoichiometric ratio). The "second event" detonator, like the burster charge, is also a high explosive weighing a few percent of the fuel weight. The reason the burster charge doesn't detonate the fuel while the detonator does, is that the fuel is not in a detonable aerosol form at the "first event." The detonator is ejected from the generic bomb shortly before the burster charge goes off. It is slowed with a suitable drag device so that it enters the aerosol cloud and detonates at the instant of fuel-air stoichiometry. An FAE weapon would be considerably more simple if this obviously very tricky procedure could be avoided by finding some way to get the fuel to self detonate the instant it reaches stoichiometry.

The effects of weather on FAE cloud formation and detonation are not very well known. Apart from some anecdotal data it has been established that temperature and humidity can change the required detonation energy by as much as 10 or 20 %.

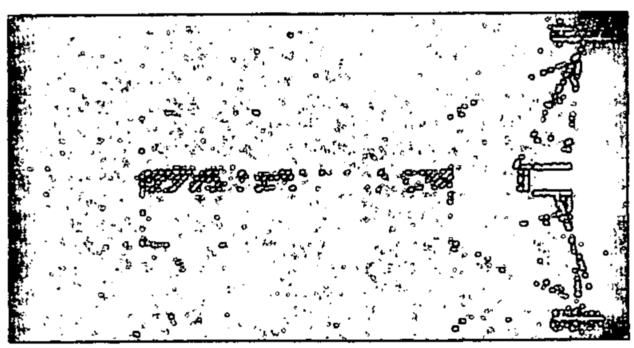


Fig. 5: Generic FAE bomb.

Safety is an important issue in weaponising FAE. Some fuels, such as aluminum powder, are benign, while others may be corrosive, unstable, inflammable, explosive, or toxic. Table V lists a few of these factors for some selected fuels. Sometimes a fuel can be selected to reduce some of these hazards. For example, the high volatility of ethylene oxide makes it difficult to contain safely at elevated temperatures. Propylene oxide is, nevertheless, a somewhat difficult material to handle and store, and could pose a fire hazard if the container leaked. Indeed, liquid fuels, in general

System	Loading Diffraction	Drag	Hard or Soft	Suitable Explosive
Tank	X		H	HE
Reinforced Bldg.	X		H	HE
APC	X		H/S	HE
SP Howitzer	X		H/S	HE
Bridge		X	H/S	HE/FAE
Missile	X	X	S	FAE
Aircraft	X	X	S	FAE
Troops	X	X	S	FAE
Antennae		X	S	FAE
Motor Vehicles	X	X	S	FAE
Unreinforced Buildings	X	X	S	FAE

HE = High Explosive
FAE = Fuel-Air Explosive

Table IV: Hard and soft targets, blast couplings, and blast sources.

are often looked upon as more haqardous than solids because of potential leakage problems. Geling the liquid is one potential method of dealing with this difficulty that is currently being investigated.

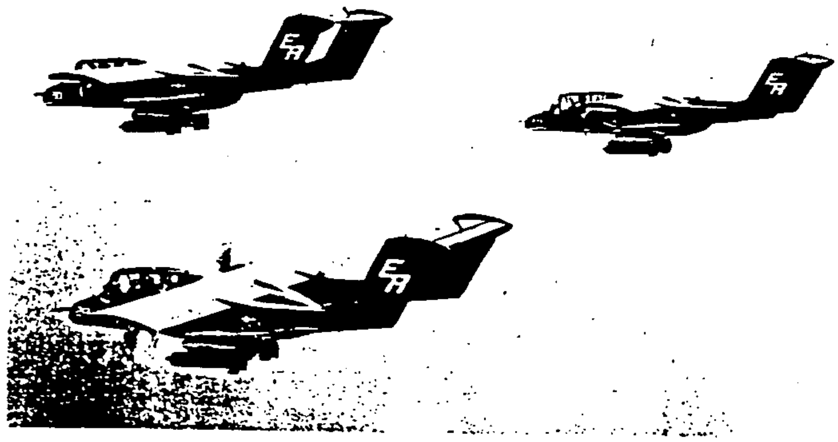
The weaponisation of FAEs is also sometimes controlled by the selection of the delivery container. If the container is already determined, for example, the weapon must be contained in a standard 226 kg (500 pound) bomb assembly, or in a 155mm artillery shell, then the quantity of fuel may be either weight or volume limited. Such constraints can give added importance to high-density fuels.

The only US FAE weapon ever fielded in battle in significant numbers was the BLU-73/B containing 33 kg (72 pounds) of ethylene oxide. It was used by the navy in Vietnam in the CBU-55/B cluster bomb. The CATFAE minefield clearing system is currently in development, but it is still several years from production. Other FAE weapons have been developed with varying success, but none have been deployed. These include the FAESHED, MADFAE, SLUFAE, HFS-I, HFS-II, BLU-95/B, and BLU-96/B. Elsewhere in the West there seems to be little interest in developing FAE weapons with no non-US programmes known to the author, except for the Canadian FALLON FAE line charge mine-clearing system. Persistent reports of Soviet FAE weapons development and use appear to be conjecture based on hearsay or anecdotal evidence, or extrapolations from normal Soviet activities in chemistry and explosive dynamics.

Table V: Safety issues for some FAE fuels.

Fuel	Corrosive	Inflammable	Explosive	Toxic
Aluminum Powder	No	No	No	No
Decane	No	Yes	No	No
Ethylene Oxide	No	Yes	No (Liquid)	Yes
Kerosene	No	Yes	No	No
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

OV-10A BRONCO, carrying three CBU-55/B FAE cluster bombs.



The FAE "gap" sometimes alluded to is probably more a worse case fear than a hard reality. In any event, the designation of Soviet or Westen FAE weapons as "second generation" or "third generation" considerably inflates the hard reality which better suggests the existence of a "1-1/2" generation at best.

Deployment and Use

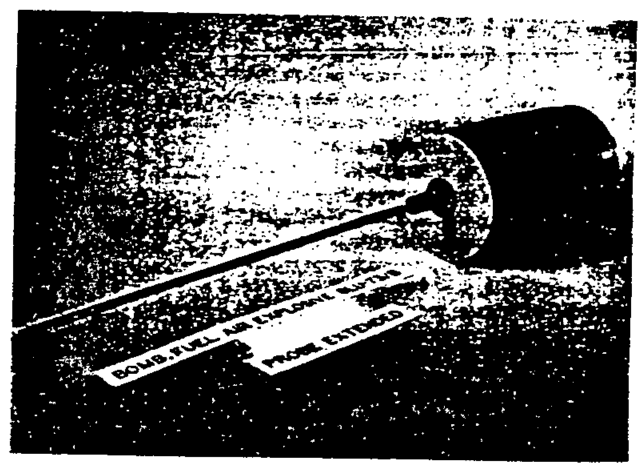
FAE weapons development has been somewhat erratic over the years. Some of this has originated from misunderstandings of the FAE phenomena, some from the difficult weaponisation problem which to some degree remains yet unsolved, and some to the West's fixation on Soviet tanks, the hardest of hard targets. FAE, of course, is not well matched against hard targets. On the other hand, there is now sufficient knowledge and experience to successfully get on with the weaponisation. As for Soviet tanks, the tactician would surely acknowledge that there are additional targets on the battlefield of comparabe importance that are ideal soft targets for FAE. For example, the loss of battalion C^3I assets could effect the battle as much as the loss of all the unit's tanks. Moreover, the global political picture is slowly changing. A study done by the International Institute for Strategic Studies has suggested that future combat is much more likely to occur where hard, armoured targets will be infrequent, but where soft targets will be the rule.

FAE weapons are sufficiently novel that the implications of their existence should be examined. FAE fuel clouds envelop targeted areas. Accordingly, the FAE projectile need not make a direct hit on the target to be effective. For example, a riveted aircraft would be unharmed if a 227 kg HE bomb exploded five metres away on the other side of the revetment. A 227 kg FAE weapon set off at the same distance would create a ten-metre radius aerosol cloud enveloping part of the revetment and the enclosed aircraft which would be severely damaged by the detonation. This means that the CEP and guidance requirements for FAE delivery systems could be considerably eased. The cost consequences of such reduced requirements could be significant.

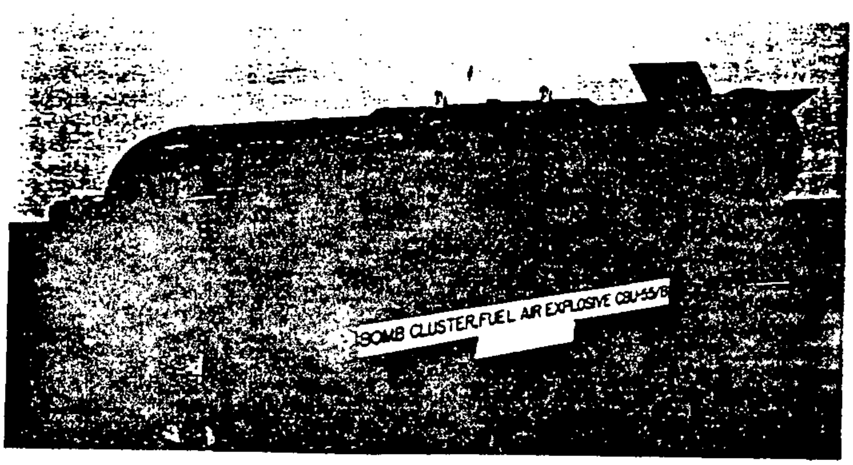
CATFAE, a mobile minefield clearing system with 21 catapult-launched rounds, each containing 63 kg (139 pounds) of FAE fuel, will penetrate conventional minefields with such ease and speed that it brings into question all future tactics that rely on conventional mine barriers. Moreover, the CATFAE rounds would be highly effective against dismounted infantry in dug-in squad and platoon positions. Foxholes and buildings provide very little protection against an enveloping FAE cloud and its blast effects. A single round could have a lethal radius of ten metres or more.

FAE as a demolition mine-clearing weapon was used in Vietnam to prepare helicopter landing sites in the jungle by clearing foliage and mines. FAE weapons used in this manner give additional flexibility to helicopter operations.

This form of explosive could become the most frequent weapon of choice in future conflicts, because it is primarily a soft-target weapons. Recent history suggests that the era of big power wars may have ended. While nuclear powers dare not attack each other, smaller nations continue manoeuvring for advantage *vis-a-vis* their neighbours and the larger powers. Conflict in such a context is more likely to present soft rather than hard targets. It is important to understand, however, that the essential area weapon characteristic of FAE gives one relativley little capacity to discriminate between targets and, therefore, precludes its efficacy in operations directly among civil populations.



The BLU-73/B FAE bomblet (right) contains 33kg of ethylene oxide. Three BLU-73/Bs are accommodated inside the CBU-55/B cluster bomb (below), the only FAE weapon ever used in battle in significant numbers.



The future of FAE and its weaponisation will depend very much on its assessed utility as a total system within the combat requirements of the West. It has potential in the classical combat context or any combat where there are identifiable soft targets. The most productive future developmental efforts will probably be in the direction of weaponisation and the creation of self-detonating fuels.

WIRE NEWS HIGHLIGHTS

MARINES SPEAK ON MISSION: A group of newly arrived Marines in Saudi Arabia expressed fears of poison gas and said they did not fully understand their mission -- but stressed they were ready to fight anyway. The Marines, from Camp Lejeune, N.C., said poison gas is a horrible, slow method of death and said they were not sure how well they would be able to fight in protective gear. There was apparent uncertainty over their role in Saudi Arabia. One said it was a politicians war while another said he thought he wasn't fighting for oil but because Saddam Hussein invaded another country. Most felt that Women Marines did not pull as much weight as male Marines. (UPI)

CZECHS SERVING IN GULF: The Czechoslovaks are the smallest ground contingent in the multinational force in Saudi Arabia, but their presence is a sign of tremendous change in the world. The 170 Czechoslovaks, who form a chemical decontamination unit, completed their deployment this weekend. It is the first time in decades that Czechoslovak troops are serving outside the former East bloc. "We are here with our small force to defend peace in this area," said Maj. Ivan Pavlov. "We are here to cooperate with the Americans and Saudis." Pavlov said the toppling of the communist government in his country means the Czechoslovaks have a new role to play in the world. That includes cooperation with the West. (AP)

OFFICIAL LEAVES PAKISTAN: A senior U.S. defense official Sunday ended a four-day visit to Pakistan during which he sought to reassure Pakistani leaders of Washington's desire to maintain close ties with its Asian ally despite fears Islamabad is developing nuclear weapons. Assistant Secretary of Defense Henry Rowen held talks with senior Pakistani civilian and military officials, including Army Chief of Staff Gen. Aslam Beg and Foreign Minister Yaqub Khan during his trip. A statement released by the U.S. embassy said Rowen "emphasized that the United States has not changed its longstanding policy of close cooperation with Pakistan on bilateral and regional issues." Pakistan -- the third largest receiver of U.S. aid -- is suspected of pushing ahead with a nuclear weapons program after the flare-up in January with rival India over the Kashmir region. India exploded a nuclear device in 1974. (UPI)

SAILORS LIGHT MENORAHS: There has never been another Hanukkah like it: Jewish-American sailors aboard the *USS John F. Kennedy* in the Red Sea, lighting candles on menorahs as they sail past countries traditionally hostile to Israel, possibly into war with an avowed enemy of the Jewish state. For the dozen or so Jewish sailors aboard the *Kennedy*, Hanukkah has been a time to reflect. For Lt. Toby Bacaner, the air wing's flight surgeon, the Persian Gulf crisis "demonstrates that whatever kind of enmity our Arab allies have for us, when the United States goes somewhere, we bring American values with us and we practice them here." In a sermon on the fourth night of Hanukkah, Rabbi Friedman, chaplain for the sixth Fleet, said, "In this momentous period of history, these lights remain as a symbol of hope, of justice, of freedom and of peace." (AP)

NO MORE AID FROM JAPAN: Japanese Finance Minister Ryutaro Hashimoto told a parliamentary committee in Tokyo Monday that the government had not been asked for more aid in connection with the Persian Gulf crisis and was not considering any. "As long as the situation in the Gulf does not change drastically, such (extra) contributions are unnecessary," he said. Japan has pledged a total of $4 billion in Gulf-related aid -- $2 billion in economic aid to Middle Eastern countries affected by the embargo and $2 billion to support the multinational force. (Reuter)

HONEYWELL PROBED: The Pentagon is investigating whether Honeywell plans for a sophisticated missile guidance system were sold to Iraq through a Swiss arms broker, the Minneapolis Star-Tribune said Sunday. The paper said it was unknown whether the Honeywell technology is in Iraqi hands . Defense Department officials said they were looking into "everything and anything" Honeywell may have done to transfer technology to Iraq. The guidance system could give missiles deadly precision. If Iraq has the technology, it could be more worrisome than its purchase of the technology to build fuel-air bombs. Weapons experts speculate that the Iraqis would employ the technology with missiles loaded with either chemical weapons or explosives such as the fuel-air bomb. (AP)

BORROWING WILL COVER GULF: President Bush's chief economic adviser, Michael Boskin, said Sunday that the government should borrow the money to pay for Operation Desert Shield. Boskin rejected demands in Congress that President Bush insist U.S. allies like Japan and Germany provide the money for the forces in the Gulf. (Reuter)

(Summarized from wire copy. Source material available at CNARS, Room 4C881.)

CHENEY...from Pg. 2

Congress gives President Carlos Menem authority to keep the vessels in the gulf if war breaks out.

Menem, the only Latin American leader to send troops to the gulf, sent Congress a bill last week asking it to allow the navy vessels to play a supporting role in an eventual war.

There were these other gulf-related developments:

- The Red Cross said in Washington that it has begun sending 375 pints of blood weekly to the gulf, for use to treat American soldiers if needed. The shipments are partly intended as rehearsal for both the Red Cross and the military in the event greater amounts of blood are required later.
- A 24-year-old Marine Corps reservist who refused to accompany his unit when it was called up for gulf duty was arrested. Lance Cpl. Eric Hayes was taken into custody by US marshals at his apartment on the campus of Southern Illinois University in Edwardsville where he is a psychology student.

Hayes, who had applied for conscientious objector status, had said that he did not want to be "a pawn in America's power play for oil profits in the Middle East."

Pentagon denies it's probing Honeywell-Iraq deal

Associated Press

Washington, D.C.

The Defense Department denied published reports Monday that it is investigating Minneapolis-based Honeywell Inc. in connection with a probe of arms technology sales to Iraq.

The Star Tribune reported Sunday that Pentagon investigators were questioning Honeywell officials about the possibility that plans for a sophisticated missile guidance system were sold to Iraq through a Swiss arms broker in 1984.

The Star Tribune article did not characterize the questioning as an investigation, but an Associated Press version of the story, based on the Star Tribune's article, did call it an investigation.

The Pentagon acknowledged that its Defense Technology Security Administration "is reviewing information on the broad question of the transfer of sensitive technology to Iraq."

"The department is specifically not investigating the Honeywell Corp. or any of its employees," the Pentagon said.

"At their own initiative, Honeywell representatives met with Defense Technology Security Administration officials here in Washington and informed them that the Honeywell company had engaged an independent law firm to audit Honeywell technology transfer policies and procedures," the Pentagon said.

Honeywell promised to provide the Pentagon with the results of the audit, it said.

Star-Tribune, pg 4 // 18 Dec. '90

Investigators are questioning Honeywell about the possibility that plans for a missile guidance system were sold to Iraq. But analysts say the alleged incident is simply one of many technology transfers during the 1980s.

Possible Honeywell data sale to Iraq probed

By Sally Apgar
Staff Writer

Pentagon investigators are questioning Honeywell executives about the possibility that plans for a sophisticated missile guidance system were sold to Iraq through a Swiss arms broker.

Weapons experts said that the possibility of Iraq possessing plans for the Honeywell guidance system could be more worrisome than Honeywell's recently reported sale of a 300-page technical study on a powerful bomb to the same Swiss arms broker. The guidance system could give any missile a deadly precision.

It is not known whether the Honeywell guidance technology is in the hands of the Iraqis, who have been scavenging technology from Western defense companies for at least six years, according to defense experts.

Two weeks ago, it was reported that Honeywell sold a study on a bomb, called a fuel-air explosive, to Iraq for $100,000 through IFAT, a Swiss company working for Argentina, Egypt and Iraq.

The 1984 sale is being examined by the Pentagon and Honeywell investigators from Covington & Burling, a Washington, D.C., law firm hired after the sale was made public.

Pentagon sources said last week that they are questioning Honeywell to determine whether one of its executives sold plans for a ring laser gyroscope to IFAT in 1984. The device is considered the heart of Honeywell guidance systems and is manufactured at its plant on Stinson Blvd. in northeast Minneapolis.

The device, which employs a system of lasers and mirrors, can be used to guide commercial or military aircraft as well as missiles. Weapons experts speculate that the Iraqis would use the technology to make guidance systems for missiles loaded with either chemical weapons or explosives such as the fuel-air explosive.

Intelligence sources believe the Iraqis are at least a year from building a nuclear bomb.

Honeywell acknowledged that investigators from the Defense Technology Security Administration met with company officials Tuesday to discuss the bomb study and other possible sales to IFAT. Pentagon officials asked the company to look for documents that would indicate whether plans for the ring laser gyroscope were sold to IFAT.

"We have not been able to find any information to support that inertial guidance technology was transferred to IFAT," Honeywell spokeswoman Susan Eich said Friday.

Clyde Bryant, chief of compliance for the State Department's Office of Defense Trade Control, said that fuel-air explosive and ring laser gyroscope technologies are "tightly controlled."

At the time of the alleged sales, Bryant said, the two technologies were on the State Department's munitions list and would have required permission and an export license from the government. Those licenses are not public.

Honeywell came under Pentagon scrutiny along with other U.S. defense contractors after five senators wrote a letter to Secretary of Defense Dick Cheney in September. They requested a Pentagon investigation to determine whether American companies sold military technology to Iraq that could be used against U.S. troops in the Persian Gulf.

Specifically, the letter questioned how fuel-air technology got into Iraqi hands. Subsequently, Honeywell was drawn into the review by reports of the bomb study sale.

The bomb, which Honeywell developed for use in Vietnam, detonates in two stages. The first disperses an aerosol cloud of fuel over a large area and the second ignites the vapor into a deadly burning cloud. Weapons experts say that within an area the size of three football fields, the bomb can flip planes or boats, demolish buildings or bunkers and kill people by

"We're looking into everything and anything Honeywell may have done transferring technology to Iraq," Defense Department spokesman Rick Oborn said last week.

Intelligence experts say that during the 1980s, Iraq became increasingly resourceful at procuring different technologies and weapons materials from the West by using several front companies and agents.

At the heart of these companies is IFAT, which is part of Consen, a network of 16 companies based in Zug, Switzerland, and Monte Carlo, Monaco.

"Zug is a nest of techno-bandits," said William Triplett, an expert on Iraqi weapons and poison gas procurement who works for the Senate Foreign Relations Committee.

"There are more fax machines and fake banks in Zug than probably anywhere else in the world."

In their letter, the senators said that Messerschmitt-Boelkow-Blohm, Germany's largest aerospace firm, may have been most directly responsible for giving the fuel-air bomb technology to the Iraqis. They noted that the alleged transfer would have occurred during the "Egyptian-Iraqi Condor II ballistic missile project to which (Messerschmitt) was a major contractor."

In 1984, Iraq, then in a death struggle with Iran, joined forces with Egypt and Argentina to procure their own version of the U.S. Pershing missile. The Iraqis are attempting to build what is believed to be a two-stage, solid-fuel rocket with a range of 620 to 650 miles. That project, known as Condor II or Bader 2000, involved the use of companies such as IFAT as fronts.

Consen, which includes scientists and engineers from Messerschmitt and other Western defense companies, supplied technical support for the three nations as they pursued several armament projects, according to investigators.

Initially, money and technology flowed in and out of Egypt. But eventually, experts believe, the three countries split and Iraq pursued the acquisition of chemical and explosive weapons systems on its own.

As Pentagon investigators attempt to trace the flow of technology and components through this web, there is much at stake for U.S. defense contractors such as Honeywell.

The senators' letter says that "should the (Pentagon's) investigation determine that any U.S. or foreign firms are culpable, contract debarment procedures would be initiated immediately."

Government officials say it appears that the bomb study did not violate regulations governing the export of military technology because it was written in a general manner. The bibliography of the study cites more than 150 public sources.

Honeywell said last week that its initial investigation also showed that the study consists "of already published, unclassified information in the public domain. Such generic information, readily available to anyone who wanted it, would by itself be far from sufficient to design or build an FAE weapon."

Honeywell said that it has encouraged employees to come forward confidentially or to use the company's ethics hot line if they have information that will aid the investigation.

Michael Butler, a Washington attorney who works on many export licensing cases, said the penalties for violating export laws are so severe that companies are extremely careful.

"There's lethal language in the regulations that basically says companies can be barred from exporting anything," he said. "A big company just can't afford to get involved in this kind of thing."

Investigators are questioning Honeywell about the possibility that plans for a missile guidance system were sold to Iraq. But analysts say the alleged incident is simply one of many technology transfers during the 1980s.

U.S. helped Iraq build technology for its arms

By Tom Hamburger
Washington Bureau Correspondent

Washington, D.C.
If it comes to war against Iraq, the United States will engage its most sophisticated military foe since World War II. And some U.S. companies and policymakers will have themselves to blame.

Iraq's advanced military capability could not have been built without foreign support, much of it from the United States. This support — in weapons, technical information and training — was not always provided surreptitious or illegally. It often was provided over the objection of Pentagon officials. It sometimes went with the blessing of the National Security Council.

"Limiting the flow to Iraq was extremely frustrating," said Stephen Bryen, former deputy undersecretary of defense for trade security during the Reagan administration. "Even the things we did see as problems ran into a great deal of pressure — pressure to release things to Iraq. We'd point out that a certain product can be used for missiles and we'd end up in big arguments with (the Departments of) State and Commerce."

President Bush has railed against the barbarism of Saddam Hussein since Aug. 2. But for seven years before Iraq's invasion of Kuwait, the Reagan and Bush administrations relaxed export restrictions to Iraq to help keep Iran in check.

Minnesota-based Honeywell Inc. recently was implicated in the possible sive (FAE) bomb technology. The FAE bomb, developed in the 1960s, is particularly effective against air bases, oil fields and troops in the open. But from the perspective of longtime military analysts, the Honeywell incident is simply one among many U.S. technology transfers to Iraq during the mid-1980s, a time when the Reagan administration was "tilting" toward Iraq.

The United States has export-control laws that closely limit shipments of weapons and require licenses for "dual purpose" goods, such as computers that could have civilian and military applications.

But these laws proved largely ineffective. "Iraq bought most of what it needed with the approval of Western governments," Bryen said.

Consider Iraq's military manufacturing and research center called Sa'ad 16. The center is used to test and build missiles, guidance systems and, possibly, nuclear weapons. Military analysts estimate that up to 40 percent of the equipment at the site was manufactured in the United States. Among the equipment is $1 million in Hewlett-Packard Co. computers and precision measurement devices. They were sold to Iraq in 1985 and 1986. Hewlett-Packard has said it had no idea the computers would be used for military purposes.

Tektronix Corp. has confirmed the sale of $50,000 worth of electronic measuring equipment to Gildemeister, the West German contractor involved in the Sa'ad plant. Wiltron Corp. has confirmed that it sold precision microwave communication test equipment to Germany for shipment to Sa'ad 16 in 1986. In each case, export licenses were issued by the U.S. government.

U.S. military technology also has been identified in newly configured Iraqi air force planes. Kenneth Timmerman, a Paris-based military analyst, told the Star Tribune that the Iraqis recently modified French-built Mirage jets so they could fire air-to-ground missiles guided by a precision laser tracking system developed by Martin Marietta Corp.

Martin Marietta says it did not sell the system to Iraq. It licensed production in the late 1970s, however, to Thomson CSF Inc., a French contractor working for the Iraqi air force.

Sales to Iraq were especially difficult to stop because U.S. strategic policies dictated that the United States should strengthen Iraq against Iran during the mid-1980s. The Defense and Commerce departments have dual responsibility to decide whether high-tech products should be exported. If the departments disagree, the decision then goes to the National Security Council at the White House. Foreign policy concerns often proved decisive in sales to Iraq.

"Our Iraq desk officers at the Defense Department were inclined to let the exports go ahead because they were trying to improve relations with Iraq," Bryen said. "They defended their clients, who told them the material would be used for scientific research. The same was true of desk officers in the State Department."

Even the man with whom Bryen most often did battle at the Commerce Department agrees. "These were not good policies," said Paul Freedenberg, a trade consultant who was the top export official at Commerce during the Reagan years.

"The U.S. government, as well as our allies, allowed and abetted the development and stockpiling of a major chemical warfare capability in the Middle East," Bryen said. "As deputy undersecretary . . . I witnessed this appalling performance and usually could do little to stop it."

Bryen recalled that while he lobbied the National Security Council to stop the sale of a computer system to Iraq in the 1980s, the Commerce Department quietly approved "export of material important to the Iraqi Sa'ad complex, such as special microwave antennas. . . . I had no way of knowing about the exports in time to stop them."

At State and Defense, officials sometime let strategic exports through on the theory that "if we don't supply them, someone else will."

The laws also failed because the Iraqis set up a system of international front companies with the goal of getting technology and raw materials that would one day enable it to manufacture weapons without depending on the West. Bryen noted that third-party shipments — through Germany and other countries — are virtually impossible to stop under the current system. It was through one of the front companies established during this project, Swiss-based IFAT Inc., that the Honeywell information allegedly was passed to Iraq.

"We could have spared ourselves this trouble today if we'd acted more vigorously back then," Bryen said.

#2

EXPAL

Defense News

July 23, 1990

SECTION: Pg. 1

LENGTH: 985 words

HEADLINE: APGM Project Grinds To a Halt In Europe

BYLINE: By CALEB BAKER, Defense News Staff Writer; Defense News correspondent Alessandro Politi contributed to this report from Rome.

DATELINE: WASHINGTON

BODY:

Problems in the transfer of sophisticated technology from the United States and sweeping defense spending cuts have forced the six remaining NATO nations to scrap development of a smart antiarmor munition, defense and industry sources in Europe and Washington say.

The $ 5 billion Autonomous Precision Guided Weapon (APGM), which originally involved more than 20 weapon makers from eight nations, is the latest weapon designed for NATO use to fall prey to budget cuts demanded by changes in the Warsaw Pact threat in Central Europe.

APGM, which was expected to double the range and accuracy of conventional projectiles fired by 155mm artillery cannons, also would have been subject to a future Conventional Forces In Europe, or CFE, treaty, because artillery cannons are expected to be withdrawn, sources say.

The demise of APGM was all but certain following the U.S. withdrawal from the project last February, European defense and industry sources say. The United States was expected to provide 39 percent of the initial funding for the smart munition, and would have supplied the millimeter-wave seeker technology critical to its development.

Canada dropped out immediately after the U.S. announcement.

In a July 13 Paris meeting of military and industry leaders in the APGM

See Page #3

project, the remaining participants agreed that they could not afford to continue the program, particularly without U.S. technology, sources say. The nations are: The Federal Republic of Germany, France, Italy, the Netherlands,

Spain and Turkey.

The decision ends four months of walvering among the APGM nations over how to restructure the program to make it less expensive, and how to balance the cost burden among all the participants, sources say. In the July 13 meeting, Italy stated a desire to drop from the project, despite West German and Dutch pleas to continue.

The nations are expected to continue limited work on APGM until October when the first phase, designed to determine the feasibility of building the advanced munition, ends. A second concept definition phase will not be funded.

In Rome, military and industry officials said last week that the fate of APGM was sealed with the U.S. withdrawal. But the decision to cancel the program was a direct result of a massive restructuring of the Italian armed forces in response to budget cuts.

Italy faced little opposition in the July 13 meeting of the APGM steering group. "Since no one wanted to pay penalties for the withdrawal from the program, we decided to issue a joint statement where everybody withdraws," one top Italian MinistrY of Defense official told Defense News.

Brig Gen. Giuseppe Capizzano, defense and air attache in the Italian Embassy here, confirmed "Italy could not go on" without U.S. participation.

One West German official says the participants "found certain difficulties in transferring technology from the United States to Europe," and thus were unable "to retain the achievements made on APGM so far." Phillip Wolfgang, head of APGM in the West German Defense Ministry in Bonn, said that the nation is likely to drop its requirement for a smart 155mm projectile.

The United States withdrew from the project after Congress deleted a $ 28.2 million Department of Defense request for APGM made in the 1990 budget. The Pentagon backed Congress' decision despite stiff opposition from some Pentagon and Army officials eager to rescue one of the U.S. military's key cooperative programs.

The U.S. withdrawal shut out European companies that would have shared the sensitive technology used in the seeker, European and Pentagon officials say. Millimeter-wave seekers operate at much higher frequencies, making them harder to jam and more effective at detecting enemy tanks.

One of the U.S. companies involved with the APGM program could have requested an export license to share some of the technology with NATO allies, sources

say. The move would have made it easier for the United States to purchase the munition after it was developed by the remaining nations, sources say.

"It is disappointing," says one Pentagon source. "I had hoped they would snub their noses at us and continue. But it is a good assumption that they could not come up with the technology."

European officials say there are alternatives to APGM that may be deployed in the 1990s. These projects include the Swedish Bonus, which has been touted as a low-cost alternative to APGM, as well as a four-nation effort to develop a smart warhead for the Multiple Launch Rocket System, sources say.

The termination of APGM is particularly hard on Italy, which decided to join the APGM project after deciding against participation in the effort to develop a new warhead for the rocket launcher. The Italian Army has fielded some 424 155mm artillery cannons.

Also, Oto-Melera, La Spezia, one of Italy's largest defense firms, considered developing an APGM-like weapon after the U.S. withdrawal, but dropped the effort because of defense spending cuts, sources in Rome say.

(c) 1990 Defense News, July 23, 1990

The consortia developing APGM are:

* The All-Weather Smart Projectile consortium, consisting of Dornier GmbH, Friedrichshafen, West Germany; Paris-based Matra; Oto Melera; Signaal, Hengelo, the Netherlands; Madrid-based Ensab; and Aselsan, Turkey. General Dynamics Valley Systems Division, Rancho Cucamonga, Calif., represented the United States, and Ottawa-based Computing Devices Co. represented Canada.

* The Alliance Development Corp., including Frankfurt-based Rhinemetall and AEG; Giat and Electronique Serge Dassault, Saint-Cloud Cedex; Rome-based Selenia S.p.A.; Amsterdam-based Fokker Aircraft; Expal, Madrid; and Turkey's Miak. The group also involved Honeywell Defense Systems Group, Minnetonka, Minn., and Hughes Aircraft Co., El Segundo, Calif. From Canada were Garrett Canada,

Rexdale; Canadian Arsenals, Ltd., Richmond; and Ottawa-based Honeywell Canada.

Defense & Foreign Affairs

July, 1988

SECTION: INDUSTRY UPDATE; Pg. 40

LENGTH: 156 words

HEADLINE: NATO Selects ADCO for APGM contract

BODY:

At a recent Source Selection Meeting held at NATO headquarters in Brussels, the Alliance Development Corporation (ADCO) was chosen for an expanded feasibility contract for the Autonomous Precision Guided Munition (APGM). The APGM program is the first major program to be funded under the Nunn Amendment.

APGM is a 155mm artillery-delivered munition which NATO has scheduled to be fielded during the mid to late 1990s as a counter to armored vehicles. The 32-month expanded contract is valued at approximately $ 100-million. Contract award was tentatively scheduled for July-August.

The Alliance Development Corporation is an international consortium composed of 12 companies based in 8 countries including: Garrett and Honeywell Ltd. of Canada; ESD and GIAT of France; Rheinmetall and AEG of Germany; Selenia of Italy; Fokker of the Netherlands; EXPAL of Spain; MKEK of Turkey; and Honeywell and Hughes of the United States.

Defense & Foreign Affairs Weekly

August 24, 1987

SECTION: LATIN AMERICA; Volume XIII, Number 33; Number 246, Third Series; Pg. 4

LENGTH: 126 words

HEADLINE: SPANISH-ARGENTINE JOINT BOMB PRODUCTION

BODY:

Spain and Argentina reportedly have agreed to establish a joint venture to produce bombs for the Argentine Air Force. The new company, named Sistemas Technologicos Aeronauticos (SITEA), will involve the Spanish bomb-manufacturer Explosivos Alaveses, of Vitoria. According to a report by the Argentine news agency TELAM, SITEA will begin with $10-million in initial capital. Financing will be shared as follows: the Argentine Defense Ministry, 49 percent; Explosivos Alaveses, 45 percent; and SITEA itself, six percent (with the Spanish Government contributing 42 percent of this six percent share). In return for providing its technological know-how, Explosivos Alaveses will receive both a share of SITEA's profits and a commision on overall sales.

LOS ANGELES TIMES

26 December

Honeywell Factor in Iraq Bomb

■ Memos show that staffers objected to the project, but the American firm provided information that helped Baghdad develop a fearsome explosive.

By DOUGLAS FRANTZ
TIMES STAFF WRITER

WASHINGTON—If U.S. troops go to war against Iraq, the deadliest weapon unleashed on them by Saddam Hussein's forces could be stamped "Made in America."

Over the objections of its own engineers, Honeywell Inc. provided agents for Iraq with technology for developing fuel-air explosives, devices 10 times more powerful than conventional weapons and considered by some experts to be "a poor man's nuclear weapons."

Along with design data for a missile warhead armed with fuel-air explosives, the 300-page Honeywell study obtained by Iraq describes ways to inflict the maximum damage and listed the most vulnerable targets—personnel, air bases, planes, naval ports, oil refineries and ships.

The story of the role played in Iraq's development of these weapons by Honeywell, one of America's biggest defense companies, illustrates what critics see as both the laxity of U.S. export controls and the peril facing U.S. troops as a result of this country's quiet aid to Iraq during its eight-year war with Iran.

The case also shows how, with such technology transfers perfectly legal and tacitly encouraged by the Reagan and Bush administrations, executives and engineers at private companies were left to use their own judgment about the proliferation of U.S. weapons technology in volatile regions such as the Mideast.

"We have made the mistake for all too long of considering some nations friends and others enemies, and we eventually find out that, in some cases, our friend is really our enemy," said Sen. John McCain (R-Ariz.), who has proposed legislation to toughen U.S. laws restricting the spread of weapons technology.

The Honeywell physicist who compiled the fuel-air explosive study in 1984 said it was sold to an intermediary for Iraq over strong objections from company insiders, an assertion supported by internal Honeywell memos. He said he omitted some potent data because he and others were worried about introducing the weapon into the Mideast.

"That it could be aimed at our soldiers is my worst nightmare come true," said Louis Lavoie, who retired from Honeywell five months ago.

Honeywell, which designed fuel-air explosive bombs for the U.S. military, sold the study to a Swiss firm acting for Iraq and Egypt, according to company documents and military and congressional sources.

At the request of five senators, the Pentagon is investigating the use of U.S. technology in Iraq's development of fuel-air explosives and other weapons. Honeywell representatives have met with investigators, but the Defense Department said it is not specifically investigating the company.

Honeywell hired an outside law firm to conduct its own inquiry into whether the technology was transferred improperly. The Minneapolis company's chairman, James Renier, said information that Honeywell's technology was provided to Iraq, first reported by NBC News, was "very disturbing."

A Honeywell spokeswoman, Susan M. Eich, said the design data obtained by Iraq appears to consist of unclassified material that was already available. She said the company does not believe that the information is sufficient to allow the building of a fuel-air explosive weapon, or FAE for short.

Yet a copy of the 1984 Honeywell FAE study obtained by The Times says the "little information available" was combined with "our own expertise in this area" to develop data for an FAE warhead for a missile.

A preliminary Pentagon review determined that no laws were violated, because the Honeywell material was not classified or restricted under export laws. Rather, in obtaining the Honeywell data, Iraq appears to have exploited regulations—something it did in more than a dozen Western countries as part of its billion-dollar campaign to develop weapons of mass destruction.

Two Iraqi efforts to buy FAE bombs from U.S. military surplus and from an American arms company were blocked by the U.S. government because the actual devices are subject to strict export controls as "significant military weapons." Instead of the bombs, Iraq bought the technology to develop its own FAEs.

This was far from an isolated example of Iraq's ambitious acquisition effort. A Senate Foreign Relations Committee report identifies 132 companies from 14 Western nations that sold military-related goods to Iraq, including 68 German firms and 10 from the United States.

A report for the Simon Wiesenthal Center in Los Angeles names 86 German firms and 18

American firms that sold equipment to Iraq that could be used to develop nuclear, chemical and biological weapons.

Much of this equipment was so-called dual-use technology, which has commercial and military applications. The U.S. government eased export controls on such devices bound for Iraq in an effort to ensure Iran's defeat in the 1980-88 Iraq-Iran War.

With U.S. troops now facing the results of this policy, Congress has tried to tighten restrictions. But last month, President Bush vetoed export-control legislation that would have imposed mandatory trade sanctions on nations that use chemical weapons. Instead, on Dec. 13 the White House announced its own plan to stem the spread of nuclear, chemical and biological weapons.

At the same time, however, Bush approved long-delayed export licenses for the sale of supercomputers to India, China and Brazil. The approval drew praise from business interests and complaints from critics worried about the potential use of the computers in designing nuclear weapons.

'That [fuel-air explosives] could be aimed at our soldiers is my worst nightmare come true.'

LOUIS LAVOIE
Retired Honeywell engineer

FAEs were developed by U.S. Navy researchers at China Lake, Calif., who exploded the first one in 1960, according to U.S. patents and the Honeywell report. The device was refined for several years before being dropped from the U.S. arsenal after the Vietnam War because it did not fit in with other strategic priorities.

The FAE device involves two precisely timed detonations. The principle is similar to filling a room with natural gas and tossing in a match.

The bomb contains fuel, usually propane or ethylene oxide, in one or more separate canisters. An initial explosion disperses the fuel over the target, resulting in a massive cloud of gas and air. The second detonation ignites the mixture, creating a huge fireball and a powerful shock wave.

The magnitude of these blasts is a subject of debate. Some experts say that FAEs are far more powerful than conventional explosives and that the resulting fireball and shock wave carry the devastation over a wide region. Others say FAEs pack little more punch than conventional explosives.

In public, the Pentagon has played down the threat from the FAEs in Iraq's arsenal, saying they do not shift the strategic balance in a potential conflict.

In simulating a near-miss with an FAE device, the Navy placed the weapon on a barge and floated it near a decommissioned destroyer escort off San Clemente Island. The distance of the blast from the ship is classified, but damage was so severe that the ship had to be towed to deep water, where it sank.

FAEs were used by U.S. forces to clear landing zones and minefields in Vietnam, and witnesses reported that even small devices leveled patches of forest the size of a football field.

FAEs are most effective in relatively flat regions—such as the desert—where the shock waves spread without interference from hills and other obstructions.

Iraq's attempts to obtain FAEs date to at least 1984, when the country was locked in its fierce war with Iran.

Iraq, Egypt and Argentina were jointly developing the Condor II, a missile with a projected 1,500-mile range. A Justice Department report said they planned to build 10 missiles in Argentina, with five each going to Iraq and Egypt. Iraq then wanted to set up its own production plant.

In 1984, the Egyptian Ministry of Defense tried to buy 9,000 surplus FAE bombs from the U.S. government, according to court records. The Egyptians claimed the bombs were to clear minefields, but a Justice Department report later said they were actually for use with the Condor II project. The request was turned down.

Simultaneously, a Swiss company called IFAT Corp. was trying to obtain FAE technology for the Condor II, according to the court records, which result from a federal criminal case in Sacramento involving arms smuggling to Egypt and Iraq. IFAT is identified in the court files as an entity established by the Egyptian Ministry of Defense as part of the Condor II project's attempt to acquire various weapons.

In mid-1984, Keith G. Smith, a British consultant to Honeywell who also worked for IFAT, approached Honeywell's aerospace and defense subsidiary in Bracknell, England, about obtaining technology for an FAE warhead.

The request to compile a study detailing how to build and use an FAE warhead was relayed to Minneapolis and eventually passed on to engineers and physicists within the aerospace and defense group.

At the time, employees at the lower levels were told that the data that was to be compiled on designing an FAE warhead would go to Egypt through a Swiss firm, according to Lavoie, the retired Honeywell physicist.

The assignment alarmed some employees because Honeywell's weapons work was done solely for the U.S. government or for foreign governments working through U.S. authorities, Lavoie said.

"It occurred to us that this might really be going to Iraq or Iran," he said. "Quite candidly, we felt that it was bad enough that it was going to Egypt. Anything of that nature going to that part of the world is dangerous."

Lavoie's supervisor, John Beckmann, objected in a memo to his boss that said, "The proposition . . . has a malodorous quality about it, [is] immoral, violates Honeywell principles and is not in the best interests of Honeywell."

Another internal Honeywell

memo called the sale of the FAE technology "a shady deal."

According to Lavoie, the complaints went up through three levels within Honeywell before the project was approved by "someone on Mahogany Row," a reference to the company's corporate executives. He said he does not know which executive actually approved the project. "Someone up the chain at Honeywell said it was OK to do, and that's the point where everything becomes a mystery," he said.

Eich, the Honeywell spokeswoman, said the outside lawyers are examining documents and interviewing current and former employees to determine how the project was approved within the company.

Lavoie said his research dealt with the chemicals and physics of creating a fuel cloud and how to detonate it. He said the analysis of the blast's effect on targets was done by Honeywell engineers at Bracknell.

During that time, Smith, the British consultant, made at least two trips to Honeywell in Minneapolis, Lavoie said. The resulting analysis was provided to Smith late in 1984, and Lavoie estimated that the price was about $200,000. Attempts to reach Smith by The Times were unsuccessful.

The copy of the Honeywell analysis obtained by The Times shows that the company developed designs for an FAE warhead and precise information about its destructive capacity. Lavoie said he "sanitized" his findings by omitting data on the most exotic and powerful potential fuels for FAEs and leaving out some equations that had been developed through research for the U.S. military.

The study is dramatic, nonetheless. It describes a warhead capable of blanketing a wide area with a death cloud using fuels "easily obtainable as output from a petroleum refinery," and details a simultaneous attack by six missiles armed with FAE warheads.

The damage inflicted by FAEs depends on the blast size and its proximity to the target. The study depicted 100% fatalities across a wide area, with injuries decreasing to lung and eardrum damage in outlying areas. Major structural damage to refineries, aircraft and ships was predicted for a large area, and a map of an airfield lists the potential damage to its various components.

A Pentagon weapons expert said FAEs are perfect for desert use.

"The flatter the better," the source said. "FAEs are a terrible danger to our troops."

Messerschmitt-Bolkow-Blohm, a major German defense firm, also provided FAE data that found its way to Iraq. A company spokesman acknowledged that MBB had provided studies and tested portions of an FAE bomb as part of the Condor II project.

The joint Iraq-Egypt-Argentina project was stopped before any missiles were built but, intelligence sources say, not before Egypt passed the FAE technology to Iraq, which continued to pursue development of FAEs on its own.

One place Iraq sought help in turning the FAE designs into weapons was Cardoen Industries, a Chilean arms manufacturer and major supplier to the Baghdad regime.

"We developed with Iraq a very close relationship when Iraq was considered to be the savior of the Western world in stopping Iran," said Fernando Paulsen, the chief spokesman for Cardoen Industries in Santiago.

He acknowledged that Cardoen built a factory in Iraq to manufacture television tubes during peacetime or electronic fuses for FAEs and cluster bombs during wartime. He said the factory was two-thirds done when Iraq invaded Kuwait on Aug. 2 and work was halted.

There is no way to determine what technology was used, but in April, 1989, Iraq displayed two FAE bombs at a weapons show in Baghdad. Pentagon sources said they do not know if Baghdad has developed a dependable FAE warhead for missiles. The missiles would be a major threat because superior American air power is expected to keep most Iraqi aircraft on the ground in the event of war. Defending against missiles would be harder.

FAEs pose another potential danger. Although the Honeywell report does not mention it, Navy researchers at China Lake designed FAEs that spew chemical and biological weapons over vast areas.

"My gut feeling is that it would work," said Elisa D. Harris, a chemical weapons specialist at the Brookings Institution in Washington. Without knowing how far U.S. research progressed in this area, Harris said, "I can't tell you whether or not FAEs would work for dispersing chemical and biological weapons. And we don't know whether Iraq has the technical ability to do it."

WASHINGTON POST

22 December

German Firms Probed for Iraq Links

U.S. Submits List of 50 Companies Suspected of Violating Embargo

By Marc Fisher
Washington Post Foreign Service

BONN, Dec. 21—The U.S. Embassy in Bonn this week gave the German government a list of 50 German companies believed to be violating the U.N. embargo against Iraq, a spokesman for Chancellor Helmut Kohl said today.

The spokesman, Dieter Vogel, said Germany already has cleared most of the companies on the list of any suspicion but is investigating other companies to see if they violated export controls, including those imposed against Iraq by the United Nations Aug. 6 in retaliation for that country's invasion and occupation of Kuwait.

A U.S. Embassy spokesman, Cornelius Walsh, refused to comment on the existence of a list.

But U.S. government sources said that the United States, using information obtained from intercepted Middle East telephone and fax communications, has given Germany evidence that some companies are continuing to do business with Iraq.

The German weekly news magazine Der Spiegel, quoting unidentified sources, will report in its next issue that the latest illegal exports involved shipments to Iraq through third countries, including Iran, Turkey and Jordan.

Der Spiegel also reports that a German company called Interatom has provided Iraq with highly sensitive nuclear technology. The magazine, quoting unnamed "officials" and "experts," said Interatom provided crucial training in uranium enrichment to Iraqi atomic researchers and machinery to be used in the construction of a nuclear test facility.

A spokesman for Interatom, which is owned by the German electronics and computer giant Siemens, denied the allegations as "completely false and baseless."

"We have never made deliveries or [provided] training in the field of nuclear technology," spokesman Hartmut Meyer told reporters.

Interatom, which builds atomic reactors, signed a contract in mid-1989 with the Industrial Projects Co. in Baghdad to provide the Iraqi firm with training and advice, the German company confirmed. Interatom began work on a pipe-construction plant in the Baghdad area but halted work when the U.N. embargo against Iraq was enacted.

Interatom said it cut off deliveries of machinery that the Iraqis said were to be used in petrochemical and pharmaceutical plants after the Bonn economics ministry notified the company last April that it had reason to question Iraqi intentions.

Vogel said the government has no evidence that Interatom made illegal deliveries.

More than 100 German companies are under investigation for allegedly violating export laws by sending nuclear or other arms technology to Iraq, according to German authorities.

The German government boasts that it has the toughest penalties in the world for export violations. But export authorities have admitted that they are virtually powerless to stop companies that circumvent the Iraq embargo by sending their materials via third countries.

MINNEAPOLIS STAR-TRIBUNE

16 December

U.S. helped Iraq build technology for its arms

By Tom Hamburger
Washington Bureau Correspondent

Washington, D.C.
If it comes to war against Iraq, the United States will engage its most sophisticated military foe since World War II. And some U.S. companies and policymakers will have themselves to blame.

Iraq's advanced military capability could not have been built without foreign support, much of it from the United States. This support — in weapons, technical information and training — was not always provided surreptitious or illegally. It often was provided over the objection of Pentagon officials. It sometimes went with the blessing of the National Security Council.

"Limiting the flow to Iraq was extremely frustrating," said Stephen Bryen, former deputy undersecretary of defense for trade security during the Reagan administration. "Even the things we did see as problems ran into a great deal of pressure — pressure to release things to Iraq. We'd point out that a certain product can be used for missiles and we'd end up in big arguments with (the Departments of) State and Commerce."

President Bush has railed against the barbarism of Saddam Hussein since Aug. 2. But for seven years before Iraq's invasion of Kuwait, the Reagan and Bush administrations relaxed export restrictions to Iraq to help keep Iran in check.

Minnesota-based Honeywell Inc. recently was implicated in the possible

(line missing)

sive (FAE) bomb technology. The FAE bomb, developed in the 1960s, is particularly effective against air bases, oil fields and troops in the open. But from the perspective of longtime military analysts, the Honeywell incident is simply one among many U.S. technology transfers to Iraq during the mid-1980s, a time when the Reagan administration was "tilting" toward Iraq.

The United States has export-control laws that closely limit shipments of weapons and require licenses for "dual purpose" goods, such as computers that could have civilian and military applications.

But these laws proved largely ineffective. "Iraq bought most of what it needed with the approval of Western governments," Bryen said.

Consider Iraq's military manufacturing and research center called Sa'ad 16. The center is used to test and build missiles, guidance systems and, possibly, nuclear weapons. Military analysts estimate that up to 40 percent of the equipment at the site was manufactured in the United States. Among the equipment is $1 million in Hewlett-Packard Co. computers and precision measurement devices. They were sold to Iraq in 1985 and 1986. Hewlett-Packard has said it had no idea the computers would be used for military purposes.

Tektronix Corp. has confirmed the sale of $50,000 worth of electronic measuring equipment to Gildemeister, the West German contractor involved in the Sa'ad plant. Wiltron Corp. has confirmed that it sold precision microwave communication test equipment to Germany for shipment to Sa'ad 16 in 1986. In each case, export licenses were issued by the U.S. government.

U.S. military technology also has been identified in newly configured Iraqi air force planes. Kenneth Timmerman, a Paris-based military analyst, told the Star Tribune that the Iraqis recently modified French-built Mirage jets so they could fire air-to-ground missiles guided by a precision laser tracking system developed by Martin Marietta Corp.

Martin Marietta says it did not sell the system to Iraq. It licensed production in the late 1970s, however, to Thomson CSF Inc., a French contractor working for the Iraqi air force.

Sales to Iraq were especially difficult to stop because U.S. strategic policies dictated that the United States should strengthen Iraq against Iran during the mid-1980s. The Defense and Commerce departments have dual responsibility to decide whether high-tech products should be exported. If the departments disagree, the decision then goes to the National Security Council at the White House. Foreign policy concerns often proved decisive in sales to Iraq.

"Our Iraq desk officers at the Defense Department were inclined to let the exports go ahead because they were trying to improve relations with Iraq," Bryen said. "They defended their clients, who told them the material would be used for scientific research. The same was true of desk officers in the State Department."

Even the man with whom Bryen most often did battle at the Commerce Department agrees. "These were not good policies," said Paul Freedenberg, a trade consultant who was the top export official at Commerce during the Reagan years.

"The U.S. government, as well as our allies, allowed and abetted the development and stockpiling of a major chemical warfare capability in the Middle East," Bryen said. "As deputy undersecretary ... I witnessed this appalling performance and usually could do little to stop it."

Bryen recalled that while he lobbied the National Security Council to stop the sale of a computer system to Iraq in the 1980s, the Commerce Department quietly approved "export of material important to the Iraqi Sa'ad complex, such as special microwave antennas. ... I had no way of knowing about the exports in time to stop them."

At State and Defense, officials sometime let strategic exports through on the theory that "if we don't supply them, someone else will."

The laws also failed because the Iraqis set up a system of international front companies with the goal of getting technology and raw materials that would one day enable it to manufacture weapons without depending on the West. Bryen noted that third-party shipments — through Germany and other countries — are virtually impossible to stop under the current system. It was through one of the front companies established during this project, Swiss-based IFAT Inc., that the Honeywell information allegedly was passed to Iraq.

"We could have spared ourselves this trouble today if we'd acted more vigorously back then," Bryen said.

MINNEAPOLIS STAR-TRIBUNE

18 December

Pentagon denies it's probing Honeywell-Iraq deal

Associated Press
Washington, D.C.

The Defense Department denied published reports Monday that it is investigating Minneapolis-based Honeywell Inc. in connection with a probe of arms technology sales to Iraq.

The Star Tribune reported Sunday that Pentagon investigators were questioning Honeywell officials about the possibility that plans for a sophisticated missile guidance system were sold to Iraq through a Swiss arms broker in 1984.

The Star Tribune article did not characterize the questioning as an investigation, but an Associated Press version of the story, based on the Star Tribune's article, did call it an investigation.

The Pentagon acknowledged that its Defense Technology Security Administration "is reviewing information on the broad question of the transfer of sensitive technology to Iraq."

"The department is specifically not investigating the Honeywell Corp. or any of its employees," the Pentagon said.

"At their own initiative, Honeywell representatives met with Defense Technology Security Administration officials here in Washington and informed them that the Honeywell company had engaged an independent law firm to audit Honeywell technology transfer policies and procedures," the Pentagon said.

Honeywell promised to provide the Pentagon with the results of the audit, it said.

LOS ANGELES TIMES Dec. 26, 1990 Pg. 1

Honeywell Factor in Iraq Bomb

■ Memos show that staffers objected to the project, but the American firm provided information that helped Baghdad develop a fearsome explosive.

By DOUGLAS FRANTZ
TIMES STAFF WRITER

WASHINGTON—If U.S. troops go to war against Iraq, the deadliest weapon unleashed on them by Saddam Hussein's forces could be stamped "Made in America."

Over the objections of its own engineers, Honeywell Inc. provided agents for Iraq with technology for developing fuel-air explosives, devices 10 times more powerful than conventional weapons and considered by some experts to be "a poor man's nuclear weapons."

Along with design data for a missile warhead armed with fuel-air explosives, the 300-page Honeywell study obtained by Iraq describes ways to inflict the maximum damage and listed the most vulnerable targets—personnel, air bases, planes, naval ports, oil refineries and ships.

The story of the role played in Iraq's development of these weapons by Honeywell, one of America's biggest defense companies, illustrates what critics see as both the laxity of U.S. export controls and the peril facing U.S. troops as a result of this country's quiet aid to Iraq during its eight-year war with Iran.

The case also shows how, with such technology transfers perfectly legal and tacitly encouraged by the Reagan and Bush administrations, executives and engineers at private companies were left to use their own judgment about the proliferation of U.S. weapons technology in volatile regions such as the Mideast.

"We have made the mistake for all too long of considering some nations friends and others enemies, and we eventually find out that in some cases, our friend is really our enemy," said Sen. John McCain (R-Ariz.), who has proposed legislation to toughen U.S. laws restricting the spread of weapons technology.

The Honeywell physicist who compiled the fuel-air explosive study in 1984 said it was sold to an intermediary for Iraq over strong objections from company insiders, an assertion supported by internal Honeywell memos. He said he omitted some potent data because he and others were worried about introducing the weapon into the Mideast.

"That it could be aimed at our soldiers is my worst nightmare come true," said Louis Lavoie, who retired from Honeywell five months ago.

Honeywell, which designed fuel-air explosive bombs for the U.S. military, sold the study to a Swiss firm acting for Iraq and Egypt, according to company documents and military and congressional sources.

At the request of five senators, the Pentagon is investigating the use of U.S. technology in Iraq's development of fuel-air explosives and other weapons. Honeywell representatives have met with investigators, but the Defense Department said it is not specifically investigating the company.

Honeywell hired an outside law firm to conduct its own inquiry into whether the technology was transferred improperly. The Minneapolis company's chairman, James Renier, said information that Honeywell's technology was provided to Iraq, first reported by NBC News, was "very disturbing."

A Honeywell spokeswoman, Susan M. Eich, said the design data obtained by Iraq appears to consist of unclassified material that was already available. She said the company does not believe that the information is sufficient to allow the building of a fuel-air explosive weapon, or FAE for short.

Yet a copy of the 1984 Honeywell FAE study obtained by The Times says the "little information available" was combined with "our own expertise in this area" to develop data for an FAE warhead for a missile.

A preliminary Pentagon review determined that no laws were violated, because the Honeywell material was not classified or restricted under export laws. Rather, in obtaining the Honeywell data, Iraq appears to have exploited regulations—something it did in more than a dozen Western countries as part of its billion-dollar campaign to develop weapons of mass destruction.

Two Iraqi efforts to buy FAE bombs from U.S. military surplus and from an American arms company were blocked by the U.S. government because the actual devices are subject to strict export controls as "significant military weapons." Instead of the bombs, Iraq bought the technology to develop its own FAEs.

This was far from an isolated example of Iraq's ambitious acquisition effort. A Senate Foreign Relations Committee report identifies 132 companies from 14 Western nations that sold military-related goods to Iraq, including 68 German firms and 10 from the United States.

A report for the Simon Wiesenthal Center in Los Angeles names 86 German firms and 18 American firms that sold equipment to Iraq that could be used to develop nuclear, chemical and bio-

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MARINES...from Pg. 7

Noriega and destroyed the Panama Defense Forces, as a last resort eeded to protect American lives. e said the death of the lieutenant was the trigger to his decision.

According to three sources who confirmed the report independently of one another, the four U.S. officers were not lost on the day of the incident.

"They knew the area very well and had been to the Comandancia many times," one source said, referring to the Panama Defense Forces headquarters.

According to another source, the men were also armed and had frequently "dared" roadblocks by driving up to them and then refusing to stop or suddenly pulling away.

"What they did this time," a source said, "was pull up to the Comandancia roadblock, knowing it was one of the most important and the guards [were] very nervous.

"When the PDF came up to them and ordered them out of the car, [the Americans] all gave them the finger," shouted an obscenity and drove off. The Panamanians then opened fire, the source said.

Another source said that although Lt. Paz was badly wounded and one of his companions was also hurt, the Americans "dumped their weapons, probably in the canal," before going to Gorgas Hospital ear Southern Command headquarters at Quarry Heights.

The sources said a report of the incident was filed with the Southern Command, which passed it on to Washington. However, they could not confirm that the report—with what they called the "true details"—ever reached Bush.

The government of Panamanian President Guillermo Endara, which was installed by the United States after the invasion and which had no role in the incident, has made no comment on the report.

In the interview, Cisneros said that officials in Panama conducted an investigation of the incident shortly after it happened.

He said interviews established that the Marines were unarmed and lost in the vicinity of the Comandancia and were not deliberately seeking to provoke an armed confrontation with the Panamanians. He said several of the Panama Defense Forces guards at the checkpoint were intoxicated.

"This was the conclusion I reached: This was another case in which PDF discipline broke down," Cisneros said. "They tried to pull [one of the Marines] out of the car. The Marines got scared and hot-rodded out of there. It looked to them like these guys [the PDF] were going to do something.

"They elected to drive away, which in retrospect probably was not smart, and the PDF opened fire," the general said.

Cisneros said he never heard of a group calling itself "the Hard Chargers" or any other such self-styled vigilante group.

"I was very strong about 'cowboying' and not doing those things," he said. "I convinced myself there was probably going to be an incident [that might lead to war between the PDF and the United States]. There was a complete breakdown of Panamanian discipline after 3 Oct., and I wanted to make sure we were on the moral and legal high ground."

Times staff writer John M. Broder, in Washington, contributed to this report.

U.S. NEWS & WORLD REPORT
Dec. 31, 1990 Pg. 20

■ **Unhappy new year.** U.S. intelligence is convinced that if war breaks out next year in the Persian Gulf, Iraq and its Libyan allies have agents in place capable of launching terrorist attacks against American and British targets in the Middle East, Europe—and even in the U.S. heartland. Based on countersurveillance evidence gathered in Turkey, Morocco and Pakistan, analysts have concluded that terrorist gangs financed by Saddam Hussein and Muammar Qadhafi already have picked their targets for a revenge offensive in case of war. The experts also worry that the terrorists have upgraded their weaponry and can now wage a "suitcase war" with new explosives designed to escape detection even by the best airport-security systems. Another concern: In some major U.S. cities, analysts believe, there are now underground cells of Islamic extremists ready to obey signals from Hussein and Qadhafi.

■ **Gulf gloom.** *Soviet military leaders are telling visitors they doubt that economic sanctions will force Saddam Hussein out of Kuwait or reduce his military capabilities. They also see no chance he will compromise on withdrawing from Kuwait, a view privately shared by the Bush administration.*

WASHINGTON POST
Dec. 25, 1990 Pg. 38

2 Sailors, Soldier Die In Mideast

Associated Press

ABU DHABI, United Arab Emirates, Dec. 24—Two sailors from the aircraft carrier USS Midway were killed when a tour bus they were riding overturned, the military's Joint Information Bureau said today.

Five other U.S. sailors were injured, two seriously, in the accident Sunday about 50 miles south of al-Dhafra airbase in Abu Dhabi.

The sailors were on shore leave, taking an off-road tour in an all-terrain bus, the military said. Helicopters from the Midway flew to assist local authorities.

One of the injured was flown to the hospital ship USS Comfort and three to the Midway. The whereabouts of the fifth were not immediately known. Names were being withheld, pending notification of next of kin.

In Saudi Arabia, the U.S. Central Command announced that one of five soldiers injured in a training accident last Thursday had died on Sunday. He was participating in a training exercise when a 105mm howitzer exploded, the military said. The soldier's name also was withheld.

WASHINGTON TIMES
Dec. 26, 1990 Pg. 6

About war

One of the most bizarre statements of the year nearly past was, surely, the claim that our troops in the Persian Gulf are there to fight for jobs and oil. Could that be true? A more outrageous motive for mass slaughter is hard to imagine. It might do for Saddam Hussein, but coming from one of our leaders such talk leads to speculation that the fellow has been to the edge and leaned too far over.

Another of our leaders, Army Lt. Gen. Calvin Waller, second in command of U.S. Persian Gulf forces, has put us on the path toward truth. He found a passage by John Stuart Mill that expresses his sentiments. Gen. Waller had the message duplicated and makes a point of handing it out to troops under his command:

"War is an ugly thing but not the ugliest of things. The decayed and degraded state . . . which thinks nothing is worth war is much worse. A man who has nothing for which he is willing to fight, nothing he cares more about than his own personal safety, is a miserable creature who has no chance of being free."

There it is. Now, the question leaders should be addressing would seem to be: What is there about the Persian Gulf situation that is worth war? Mill suggests the correct answer must have something to do with freedom, a matter somewhat more worthy of extreme sacrifice than jobs and oil.

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logical weapons.

Much of this equipment was so-called dual-use technology, which has commercial and military applications. The U.S. government eased export controls on such devices bound for Iraq in an effort to ensure Iran's defeat in the 1980-88 Iraq-Iran War.

With U.S. troops now facing the results of this policy, Congress has tried to tighten restrictions. But last month, President Bush vetoed export-control legislation that would have imposed mandatory trade sanctions on nations that use chemical weapons. Instead, on Dec. 13 the White House announced its own plan to stem the spread of nuclear, chemical and biological weapons.

At the same time, however, Bush approved long-delayed export licenses for the sale of supercomputers to India, China and Brazil. The approval drew praise from business interests and complaints from critics worried about the potential use of the computers in designing nuclear weapons.

FAEs were developed by U.S. Navy researchers at China Lake, Calif., who exploded the first one in 1960, according to U.S. patents and the Honeywell report. The device was refined for several years before being dropped from the U.S. arsenal after the Vietnam War because it did not fit in with other strategic priorities.

The FAE device involves two precisely timed detonations. The principle is similar to filling a room with natural gas and tossing in a match.

The bomb contains fuel, usually propane or ethylene oxide, in one or more separate canisters. An initial explosion disperses the fuel over the target, resulting in a massive cloud of gas and air. The second detonation ignites the mixture, creating a huge fireball and a powerful shock wave.

The magnitude of these blasts is a subject of debate. Some experts say that FAEs are far more powerful than conventional explosives and that the resulting fireball and shock wave carry the devastation over a wide region. Others say FAEs pack little more punch than conventional explosives.

In public, the Pentagon has played down the threat from the FAEs in Iraq's arsenal, saying they do not shift the strategic balance in a potential conflict.

In simulating a near-miss with an FAE device, the Navy placed the weapon on a barge and floated it near a decommissioned destroyer escort off San Clemente Island. The distance of the blast from the ship is classified, but damage was so severe that the ship had to be towed to deep water, where it sank.

FAEs were used by U.S. forces to clear landing zones and minefields in Vietnam, and witnesses reported that even small devices leveled patches of forest the size of a football field.

FAEs are most effective in relatively flat regions—such as the desert—where the shock waves spread without interference from hills and other obstructions.

Iraq's attempts to obtain FAEs date to at least 1984, when the country was locked in its fierce war with Iran.

Iraq, Egypt and Argentina were jointly developing the Condor II, a missile with a projected 1,500-mile range. A Justice Department report said they planned to build 10 missiles in Argentina, with five each going to Iraq and Egypt. Iraq then wanted to set up its own production plant.

In 1984, the Egyptian Ministry of Defense tried to buy 9,000 surplus FAE bombs from the U.S. government, according to court records. The Egyptians claimed the bombs were to clear minefields, but a Justice Department report later said they were actually for use with the Condor II project. The request was turned down.

Simultaneously, a Swiss company called IFAT Corp. was trying to obtain FAE technology for the Condor II, according to the court records, which result from a federal criminal case in Sacramento involving arms smuggling to Egypt and Iraq. IFAT is identified in the court files as an entity established by the Egyptian Ministry of Defense as part of the Condor II project's attempt to acquire various weapons.

In mid-1984, Keith G. Smith, a British consultant to Honeywell who also worked for IFAT, approached Honeywell's aerospace and defense subsidiary in Bracknell, England, about obtaining technology for an FAE warhead.

The request to compile a study detailing how to build and use an FAE warhead was relayed to Minneapolis and eventually passed on to engineers and physicists within the aerospace and defense group.

At the time, employees at the lower levels were told that the data that was to be compiled on desig- ing an FAE warhead would go to Egypt through a Swiss firm, according to Lavoie, the retired Honeywell physicist.

The assignment alarmed some employees because Honeywell's weapons work was done solely for the U.S. government or for foreign governments working through U.S. authorities, Lavoie said.

"It occurred to us that this might really be going to Iraq or Iran," he said. "Quite candidly, we felt that it was bad enough that it was going to Egypt. Anything of that nature going to that part of the world is dangerous."

Lavoie's supervisor, John Beckmann, objected in a memo to his boss that said, "The proposition . . . has a malodorous quality about it, [is] immoral, violates Honeywell principles and is not in the best interests of Honeywell."

Another internal Honeywell memo called the sale of the FAE technology "a shady deal."

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The study is dramatic, nonetheless. It describes a warhead capable

BOMB...Pg. 15

ISRAEL...from Pg. 11

missile program because of intensified threats from Iraq.

A flight test of the Arrow took place a week after Iraq launched its Aug. 2 invasion of Kuwait.

Earlier this year, Mr. Hussein threatened to "burn half of Israel" if attacked by Israel.

The Arrow is a two-stage, high-speed interceptor missile that is being developed jointly by the United States and Israel. Officials said testing is nearing completion and that the missile program would then enter full-scale development. Iraq has said it wants the Arrow included in any regional proposals banning nuclear, biological and chemical weapons from the Middle East.

The Israeli ABM test follows a recent test-firing of an Israeli Jericho I missile from a South African military base in late November. The last test of a Jericho II, a two-stage missile with a range of about 1,000 miles, took place in January.

The Jericho II is believed by military experts to be the primary delivery system for Israel's nuclear arsenal.

The Jericho I test is viewed by U.S. intelligence agencies as a further indication of Israeli-South African cooperation in developing long-range missiles.

The South Africans test-fired a modified Jericho II missile last year with a 900-mile shot into the Indian Ocean.

The U.S. government has held talks with the Israelis in an effort to halt their cooperation with South Africa because of opposition to that nation's racial policies.

Israel said several years ago that it would sign no new military contracts with the South Africans, but has declined to discuss ongoing joint programs.

EUROPE...from Pg. 4

of the arms as if they had remained in central Europe—in effect, holding a spot open for their eventual return. "There is still a balance-of-power equation in terms of Europe that has to be kept in mind," Secretary of State James A. Baker III said on ABC News several weeks ago.

Galvin, perhaps reflecting some local anxieties, noted that the transfer of these forces to the gulf, in combination with a congressionally ordered cut of another 50,000 U.S. military personnel in Europe, "is going to take us down to quite low numbers." He said the services were discussing a proposal to obtain a presidential exemption from the reduction.

Cheney similarly told the House Armed Services Committee two weeks ago that "we are in a bit of a paradox—on the one hand undertaking massive military movement and commitment, preparing for the possibility of hostilities in a major way, while simultaneously preparing a budget . . . that provides for . . . a significant reduction in U.S. military force structure and capability."

Cheney said he may seek relief from the personnel restrictions voted by Congress when he submits a supplemental budget request in late January or early February for Operation Desert Shield. But such a proposal could ignite a fierce debate.

Rep. Patricia Schroeder (D-Colo.), a member of the House Armed Services Committee, said of the transferred troops: "I don't think they're ever coming back [to Europe]. How in the world can we justify our . . . [remaining] there in those [old] numbers?" Sen. John Glenn (D-Ohio), who chairs the Senate Armed Services manpower and personnel subcommittee, said, however, that he was willing to let some of the troops "go back to Europe" if they were not needed in Saudi Arabia and had not completed their normal tour of duty.

Staff writer George C. Wilson contributed to this report.

WASHINGTON TIMES Dec. 25, 1990 Pg. 8

Defense map makers inundate U.S. troops

ST. LOUIS (AP) — Operating at a wartime pace, the U.S. Defense Mapping Agency says it has shipped 35 million maps to the nearly 300,000 U.S. troops stationed in the Persian Gulf.

That may seem like overkill. But the military needs maps of varying detail and intricacy, with many to be used once and discarded, the agency says.

"We certainly hope it doesn't come to war, but if it were to become a hostile action, we want our troops to have the best products they can," said Dave Black, the agency's director of public affairs. "When the Joint Chiefs of Staff lay out the requirements, we meet them."

Cartographers at the agency's two major production centers in St. Louis and Brookmont, Md., have been working 10- to 12-hour shifts, seven days a week, since shortly after the United States began sending troops to the Persian Gulf as part of Operation Desert Shield.

They worked round the clock through Labor Day and Thanksgiving, and there might not be any extra time at home for Christmas — not with a Jan. 15 deadline for Iraq to get out of Kuwait or face possible military action.

All of Saudi Arabia, Kuwait and Iraq has been committed to paper, Mr. Black said. The agency has had every country in the volatile Middle East mapped for several years, relying heavily on detailed satellite photos.

About 4,500 different maps have been used in the territory covered by Operation Desert Shield, breaking down the topography into relatively small coverage areas for pilots, tank commanders, admirals and ground troops.

Generally, pilots need the big picture. But pilots of low-flying aircraft — including helicopters and jets launched from aircraft carriers — need more specific information about hills and other terrain than bomber pilots. Soldiers on the ground need to know where roads and power lines are.

The number of maps shipped to the Gulf include countless spares. Pilots might mark out a mission on a map, then discard it. Ground troops do likewise for another reason.

"You've got these things folded up and stuffed in your pocket, so after a sweaty day in the desert they literally come apart," said A. Clay Ancell, deputy director in charge of production at the center in St. Louis, where

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of blanketing a wide area with a death cloud using fuels "easily obtainable as output from a petroleum refinery," and details a simultaneous attack by six missiles armed with FAE warheads.

The damage inflicted by FAEs depends on the blast size and its proximity to the target. The study depicted 100% fatalities across a wide area, with injuries decreasing to lung and eardrum damage in outlying areas. Major structural damage to refineries, aircraft and ships was predicted for a large area, and a map of an airfield lists the potential damage to its various components.

A Pentagon weapons expert said FAEs are perfect for desert use.

"The flatter the better," the source said. "FAEs are a terrible danger to our troops."

Messerschmitt-Bolkow-Blohm, a major German defense firm, also provided FAE data that found its way to Iraq. A company spokesman acknowledged that MBB had provided studies and tested portions of an FAE bomb as part of the Condor II project.

The joint Iraq-Egypt-Argentina project was stopped before any missiles were built but, intelligence sources say, not before Egypt passed the FAE technology to Iraq, which continued to pursue development of FAEs on its own.

One place Iraq sought help in turning the FAE designs into weapons was Cardoen Industries, a Chilean arms manufacturer and major supplier to the Baghdad regime.

"We developed with Iraq a very close relationship when Iraq was considered to be the savior of the Western world in stopping Iran," said Fernando Paulsen, the chief spokesman for Cardoen Industries in Santiago.

He acknowledged that Cardoen built a factory in Iraq to manufacture television tubes during peacetime or electronic fuses for FAEs and cluster bombs during wartime. He said the factory was two-thirds done when Iraq invaded Kuwait on Aug. 2 and work was halted.

There is no way to determine

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Counting Up the Atrocities

By MICHAEL KRAMER

Was the Kuwaiti supermarket manager shot to death by Iraq's occupation forces? Or was he beheaded? Or hanged? Three supposed eyewitnesses described the murder differently to TIME, although all agree on the result: the man is definitely dead. Whatever actually happened, the fate of that particular Kuwaiti confirms a well-known reality: truth is often war's first casualty.

Among those who monitor atrocities for a living, a dispute is simmering. How many Kuwaitis have been summarily executed since Iraq's invasion on Aug. 2? How many have been tortured, how many arrested, how many raped? No one knows for sure, and few but Saddam's henchmen may ever know.

At one level, the debate concerns intellectual honesty. At least one human-rights organization believes the Kuwaiti government in exile may be orchestrating exaggerated tales of horror for political gain. "The situation is bad enough when you consider just the tragedies that can be objectively verified," says Andrew Whitley, the executive director of Middle East Watch, headquartered in New York. "There is no need to inflate the statistics."

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WIRE NEWS HIGHLIGHTS

SPEECH NOT ANTI-WEST: KGB Chairman Vladimir Kryuchkov said Tuesday his weekend speech warning of foreign economic sabotage had been misunderstood and vowed the Soviet Union will not return to the Cold War era of denunciations. "It is impossible to return to the past, in the Soviet Union or abroad," he said at a news conference. "If someone wanted to try to return to the past in the Soviet Union, he would fail miserably." His speech Saturday before the Soviet congress was widely seen as a return to Cold War rhetoric. He accused the CIA and other foreign agencies of attempting to "impose doubtful ideas and plans" on the Soviet Union. Hew said some foreign businessmen were engaged in economic sabotage. The U.S. State Department denounced the speech and said there was no truth to it. (UPI)

EXPLOSION NEAR ROME CLUB: A rudimentary explosive device, probably a large firework, went off early Tuesday near a U.S. servicemember's club in Rome causing slight damage and no injuries, police said. The blast, in an alleyway near the Vatican, shattered the glass doors of a rear entrance to the music academy of St. Cecilia. It also caused slight damage to the rear of the United Service Organization and to the studios of Vatican Radio. Both were closed at the time. Police said it was not clear which organization was the target of the blast and there was no claim of responsibility. (Reuter)

GUERRILLAS DESTROYS BOATS: Leftist guerrillas destroyed two naval vessels in separate attacks in the Amazon region of Colombia Tuesday. In addition, a policeman and a rebel were killed when guerrillas attacked a police column in the district of Miraflores, 350 km south of Bogata. The actions were carried out by the FARC and ELN guerrilla groups. The groups recently joined forces to negotiate peace terms with the government. (EFE)

U.N. WOULD MEET BEFORE WAR: French Defense Minister Jea Pierre Chevenment said Tues. he thought the United Natio. Security Council would convene again before resorting to military action to drive Iraq from Kuwait. "I think events will bring it to do so," he said during a television interview when asked if the Council needed to meet again before the Jan. 15 deadline to Iraq. Chevenment -- who was in Saudi Arabia visiting French troops -- said the U.N. deadline could not be pushed back unless new developments take place. (Reuter)

RYZHKOV SUFFERS HEART ATTACK: President Mikhail Gorbachev said Soviet Prime Minister Nikolai Ryzhkov had suffered a heart attack but his life was not in danger. Gorbachev made the announcement at the start of the morning session of the Congress of People's Deputies Tuesday. (Reuter)

(Summarized from wire copy. Source material available at CNARS, Room 4C881.)

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crew of one of its planes when it crashed during a training exercise. It was Colonel Robinson's job to return to the United States briefly to present flags to the families of B. K. Henderson, a chemical engineer from Molton, Ala., and Steve Schramm, an engineer with the Southern Company here.

"It was the toughest thing I have ever had to do," he said.

Col. James F. Brown, the commander of the 117th, who arrived back in the United States two days ago, said all 115 men from the unit who went to the Persian Gulf had volunteered and about 20 percent of them had been part-time soldiers, as opposed to full-time military employees attached to the unit, like Colonel Brown.

With a new rotation schedule in effect that puts each of the units in the gulf for three to six months at a ti.. the Birmingham-based unit's next rotation into the region would be in the spring of 1992.

"But I hope we're not needed," said Colonel Robinson. "It's a foolish man who wants to go to war."

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what technology was used, but in April, 1989, Iraq displayed two FAE bombs at a weapons show in Baghdad. Pentagon sources said they do not know if Baghdad has developed a dependable FAE warhead for missiles. The missiles would be a major threat because superior American air power is expected to keep most Iraqi aircraft on the ground in the event of war. Defending against missiles would be harder.

FAEs pose another potential danger. Although the Honeywell report does not mention it, Navy researchers at China Lake designed FAEs that spew chemical and biological weapons over vast areas.

"My gut feeling is that it would work," said Elisa D. Harris, a chemical weapons specialist at the Brookings Institution in Washington. Without knowing how far U.S. research progressed in this area, Harris said, "I can't tell you whether or not FAEs would work for dispersing chemical and biological weapons. And we don't know whether Iraq has the technical ability to do it."

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aeronautical maps are made. Maps for land and sea are produced at Brookmont.

Nearly every soldier in the desert has some sort of map. The first ones began arriving in Saudi Arabia about a week after the first U.S. troops landed there.

Thanks to improved technology, map production already has gone beyond what was done during the Korean and Vietnam wars.

"During the Korean War, the presses ran 24 hours a day, seven days a week for years," said Otto Stoessel, graphic arts chief of the aerospace division. "We turned out a lot of work, but compared to Operation Desert Shield it was nothing.

"We've done 10 times the amount of work in the last two months than we did during all of Korea," he said.

About 8,000 people are employed at the centers in St. Louis and Brookmont, and even before the Persian Gulf crisis they were busy, said Mr. Ancell.

Maps constantly must be updated, and in August the agency also was busy making maps used in the nation's battle to stop the flow of drugs from South America.

ATROCITIES...

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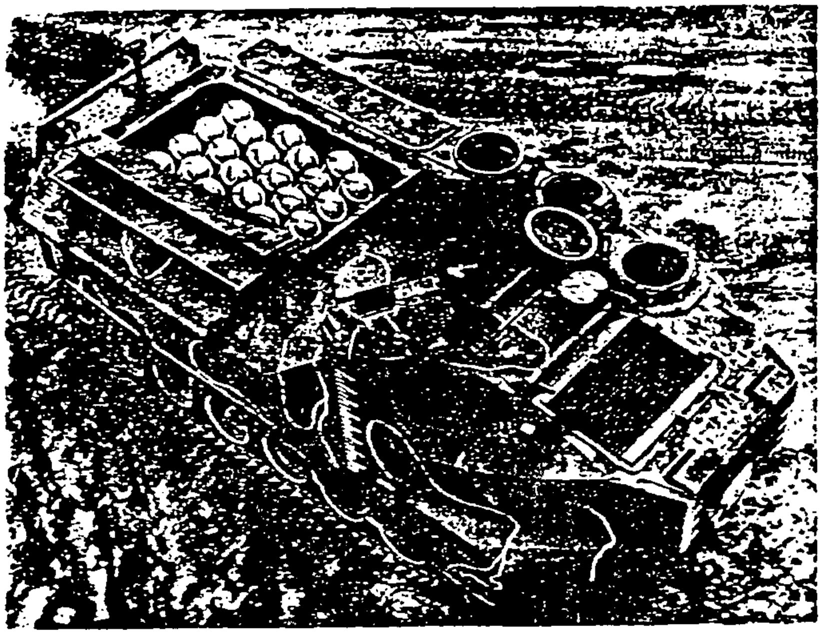
The human-rights organizations are quarreling among themselves. Middle East Watch, for example, contends that the recent report by Amnesty International detailing human-rights abuses in Kuwait is overdrawn. But the problem is one of degree only. When Middle East Watch says Amnesty's high-range estimate of perhaps a thousand murders exaggerates the toll by about 400, that still leaves 600 victims of Iraqi brutality. And no one disputes that Iraq has regularly tortured Kuwaitis. Again, the only difference involves numbers.

The account by London-based Amnesty International is crucial because it has dramatically affected the world's most important audience. Days after reading the 82-page report at Camp David, George Bush was still talking about it. "I ask you to read half of it," said the President during an interview with TIME in the Oval Office. "If you can't stomach half of it, read a quarter of it."

Far more than the number of atrocities, the manner of Iraq's barbarism has stuck with Bush. Amnesty documents 38 methods of torture used by the Iraqis—everything from the use of electric probes to the cutting off of ears and tongues. "Good God," says Bush, "it is so powerful, you won't be able to believe it."

Human-rights reports are political documents. They are embraced or ignored depending on the interests of nations. Amnesty, for one, has regularly detailed the torture, detention and murder of Iraqis—by Iraqis—but the U.S. hardly cared about such atrocities during the years when Washington's Middle East policy dictated accommodating Saddam. So when the President says Amnesty's report has "really made an impression on me," he is reacting in a new context. Had he been applying a consistent human-rights standard all along, he would have been just as exercised about last year's Amnesty report on Iraq, and perhaps the Administration would have supported the sanctions some Congressmen were urging be Saddam's brutality spilled beyond Iraq's borders.

More important, the U.S. may now move militarily—without giving the sanctions time to work on Saddam—because the President describes the Amnesty report as "one of the things that's driving me. I've heard some guy telling me ... we've got time. Time. Read it. It's what's happening now. We don't have a lot of time."



The latest operational application of FAE is the CATFAE (Catapult-Launched FAE) mine-clearing system, currently under development for the USMC.

Louis Lavoie

Fuel-Air Explosives, Weapons, and Effects

A fuel-air explosive (FAE) is, by definition, a detonable material that gets most, or all, of its required oxygen from the air. Two almost unique properties of FAE are that it carries little or no oxygen with it, thereby giving it good weight efficiency, and that the detonation occurs over a significant area thereby generating a greater impulse than with a point detonation characteristic of conventional high explosives. Exceptions to the latter point, that will not be discussed in detail here, are dispersed, conventional high explosive powders, and nuclear explosives.

Reports of Soviet use of FAE in Afghanistan have revived interest in FAE weapons by the US military after several years of relative neglect. The zenith of US development may have been reached in January 1973 with the detonation of an FAE device next to the decommissioned destroyer escort, USS MCNULTY, which eventually caused it to sink. However, at least 13 years earlier work was in progress at the China Lake Naval Weapons Center which, by the late 1960s, led to operational tests in Vietnam and the design of the CBU-55/B containing 3, BLU-73/B FAE bombs. Since the late 1970s interest in FAE weapons has declined except for the CATFAE minefield clearing system and the stillborn SLUFAE, also intended for mine clearing. What are fuel-air explosives, how do they work, and why have they alternately excited and disappointed the military community? In this article we will try to answer these questions as well as address the issues of weaponisation, and tactical application

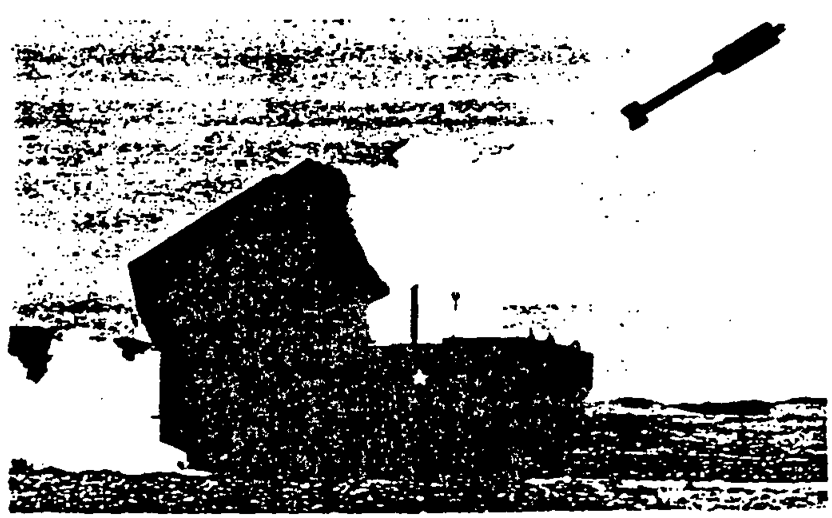
Mr. Lavoie is a defence analyst for the Defense Systems Group of Honeywell Inc., in Minnesota.

Technical Background

Precisely as the name implies, fuel-air explosives are explosives that rely on oxygen in the air as the primary source of the indispensable oxidizing agent. Several early references in the literature otherwise, are incorrect. For example, FAE detonation in space is a contradiction in terms. Other early references to FAE "burning" in an oxygen-free environment are beside the point, since "burning" and "detonation" are not the same thing. Burning is "slow" oxidation (rusting iron is even slower yet) while detonation is very quick, propagating through the reacting medium at velocities of several kilometres per second.* The fuel-air explosion process contrasts to that of conventional high explosives, such as TNT, which carry adequate oxygen already attached to the explosive molecule (Figure 1). It should be noted, however, that the energy output of conventional high explosives can be boosted by adding oxidizer if their molecules are naturally oxygen lean (TNT), or by adding a reducing agent such as aluminum, if fuel lean (ammonium nitrate). In some cases the additional oxidizer can come from the air just as with FAE. Indeed, some of these explosives, when dispersed as powders, are coming to be grouped with FAE and other high impulse explosives under the name of enhanced blast munitions (EBM).

Fuel-air explosives are more weight efficient than conventional explosives since they obtain their oxygen from the air. Figure 1 shows that 42 % of the weight of TNT is due to the oxygen it must carry with it while 41 and 47 % of the weight of the consumables (fuel and oxygen) in, respectively, propylene oxide/air or aluminum dust/air explosions, comes from the

** Some FAE fuels, for example ethylene and propylene oxides, have an oxygen atom in the molecule and, indeed, can exothermally decompose in the absence of air, but they don't detonate. Also contrary to some references in the defence literature, many FAE fuels are relatively benign e.g. kerosene.*

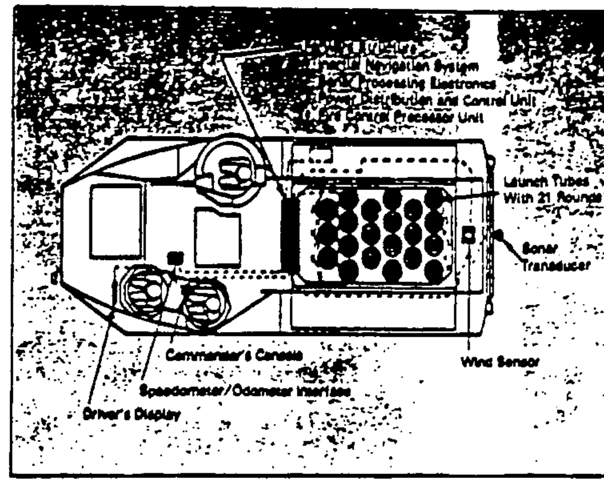


SLUFAE was an earlier US attempt at FAE for mine-clearing purposes.

a.: and is not carried with the explosives. Accordingly, weight for weight propylene oxide and aluminum release 7.9 and 7.4 times as much energy as TNT (Table I).

There are many possible FAE fuels, but practical onsiderations such as safety quickly reduce the list. The unclassified list of known detonable FAE fuels is not very large. Hydrocarbons are the most numerous. Table II lists some of those that have been demonstrated to detonate as well as including non-hydrocarbon fuels. Indeed, hydrocarbons attracted early civil attention to the FAE phenomenon because of accidents in the petroleum industry.

Arrangement of a CATFAE vehicle (AAVP-7A1 hull).



Below: Fig. 1: Idealised chemical reactions of exploding TNT and FAE fuels.

100 kg TNT:

$$12\,C_6H_2CH_3(NO_2)_3 \rightarrow 14\,CO_2 + 24\,CO + 48\,C + 17\,N_2 + 20\,H_2O + 7\,H_2 + 2\,NH_3$$

42 kg O_2

100 kg Propylene Oxide:

$$C_3H_6O + 4\,O_2 \rightarrow 3\,CO_2 + 3\,H_2O$$

69 kg from the air

100 kg Decane:

$$2\,C_{10}H_{22} + 3O_2 \rightarrow 20\,CO_2 + 22\,H_2O$$

34 kg from the air

100 kg Aluminum Powder:

$$4\,Al + 3O_2 \rightarrow 2\,Al_2O_3$$

89 kg from the air

Fuel	kcal/g	kcal/cm^3
Decane	11.3	8.5
Kerosene	10.2	8.2
Propylene Oxide	7.9	6.6
Aluminum (powder)	7.4	11*
Ethylene Oxide	6.9	6.0
TNT	1.1	1.6

* Although elemental aluminum has a density of 2.7 the bulk powder densities are significantly less, typically in the range of 0.8 to 1.5 g/cm^3.

Table I: Specific energy of some FAE fuels.

No theory of detonation exists that can predict the detonability of a potential FAE material. Many fuels will burn (deflagrate) without detonating. Others will only detonate if suitably excited by a powerful enough source, and some will detonate quite easily. The critical detonation energy depends on the type of fuel, the fuel particle or drop size if it is solid or liquid, the energy deposition rate (power), the fuel-air ratio, and, to a lesser extent, the temperature and humidity. A useful rule of thumb is that an FAE detonator should contain a conventional explosive mass about 1 % of the FAE mass.

FAE as Weapons

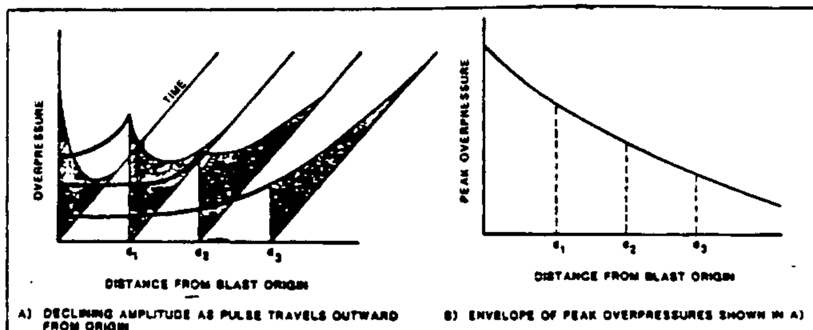
The weaponisation of fuel-air explosives would be greatly simplified if a good way could be found to cause the fuel to self detonate at the right moment. Thus far research in this area has been only slightly successful with fairly impractical results achieved by injection of highly reactive fluorine or bromine trifloride into the fuel cloud causing detonation. Some progress is also being made with autodetonating gelled fuels.

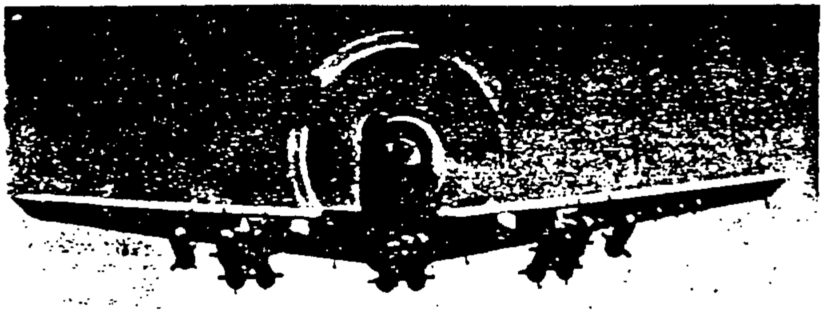
Apart from nuclear weapons, pure blast weapons are believed by some in the defence community to be relatively ineffective unless augmented with penetrators, fragmentation, incendiary, or other damage-producing agents. Nevertheless, FAEs are effective precisely because of their blast. To understand this apparent contradiction it is necessary to use more exact terms than "blast" and to relate these new terms to target vulnerability.

The blast produced by any explosive can be characterised by peak overpressure and impulse* at a given distance from the centre of the detonation. Overpressure is the pressure increase above normal ambient caused by the heated and expanding products of the explosive chemical reaction. At a point some distance from the blast origin the passing blast wave will cause the pressure to abruptly increase from ambient to some peak value, then decay relatively slowly back to ambient. The greater the distance from the origin of the blast, the less the peak overpressure of the passing wave (Figure 2). Impulse at these same measurement points is the product of the overpressure and the duration of its application. If the overpressure occurred as a square wave, the impulse would be calculated as just overpressure times its duration. But overpressure decays exponentially, so its waveform appears more triangular than square. Accordingly, an exact expression for impulse requires the time integration of overpressure (I = ? P dt.) However, in some cases it is adequate to assume the overpressure pulse is shaped like a right triangle and compute the impulse as the area of the triangle (I = 0.5 Pt)

* *The term "impulse," is used here as it is generally used in the blast and vulnerability literature, which is strictly speaking, impulse per unit area. Of course, true impulse is the time integral of force.*

Fig. 2: Pulse shape in space and time of blast over pressure.





where "t" is the decay time constant. There are several factors that establish the duration of the overpressure pulse, and hence the impulse, including the quantity, energetics, spatial distribution of the exploding material, and the distance from the centre of the explosion. Useful approximations for computing FAE overpressure and impulse are given in Table III.

Blast waves load targets through diffraction and drag coupling. Targets are damaged in diffraction loading because of the pressure differences that appear across them as the blast wave passes. The coupling is optimum when the blast wave duration is less than one fourth the natural vibration period of the target. Lightweight targets have short periods. This implies short, high-pressure blasts are needed to damage them, since the period is proportional to the square root of the target mass. Accordingly, diffraction-dominated coupling is most effective against overpressure sensitive targets

Acetylene
Aluminum
Butane
Decane
Ethane
Ethylene
Ethylene Oxide
Heptane
Kerosene
Methane
Propane
Propylene
Propylene Oxide

Above: This Vietnam-era photo depicts a SKYRAIDER carrying 14 CBU-55/B FAE bombs.

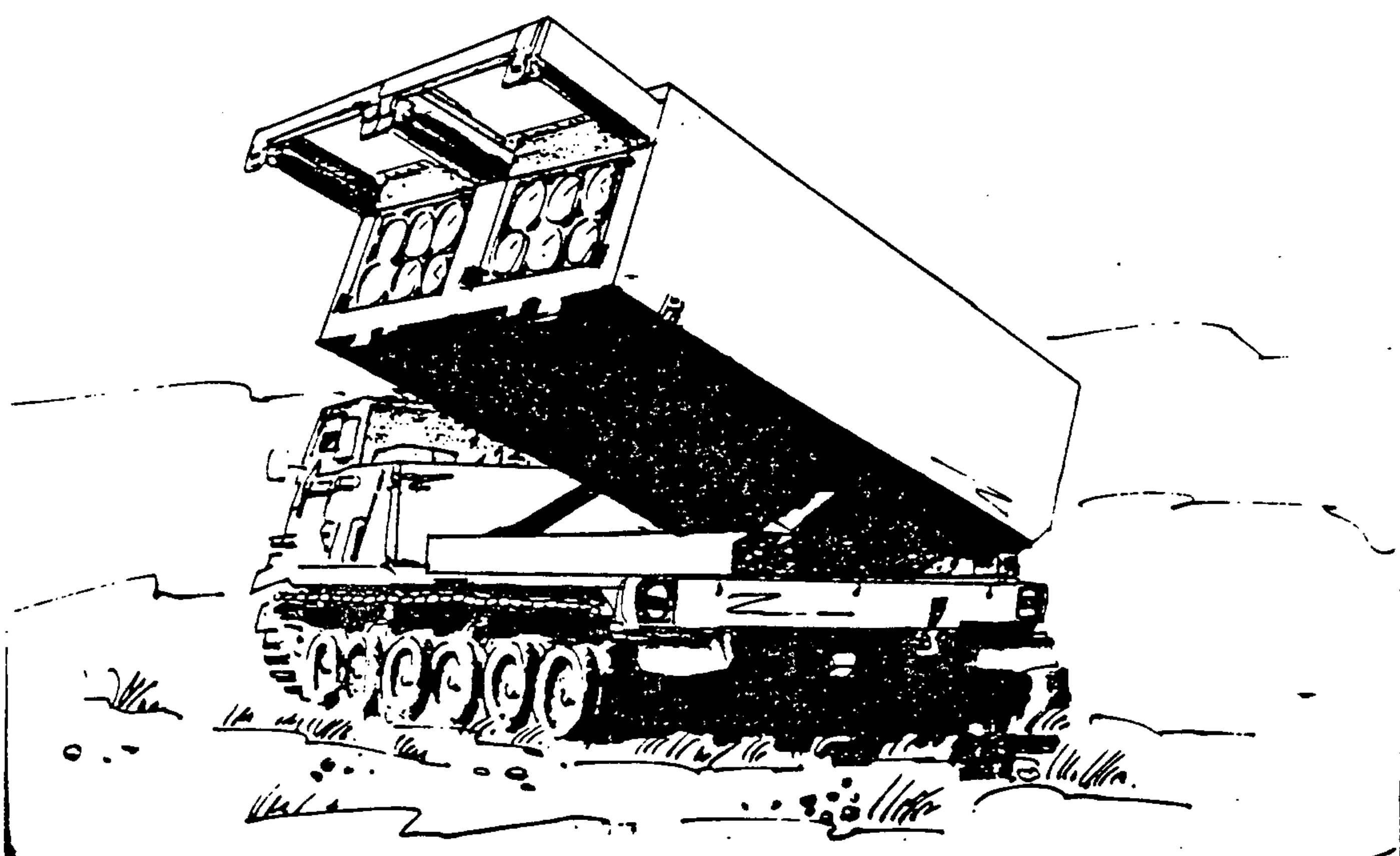
Table II: Some possible FAE fuels that have been successfully detonated.

Targets are damaged by drag loading because of the drag resistance to the air moving rapidly over them. Drag load damage increases in proportion to the duration of the blast. Since impulse is the product of overpressure and time, it is clear that impulse dominated blast loading is most effective against drag-sensitive targets. Drag-sensitive targets are usually considered "soft," while diffraction-sensitive targets are usually considered "hard" (Table IV).

Many targets are vulnerable to both diffraction and drag loads. For example, an automobile exposed to a blast with its windows closed might have its roof crushed and windows broken by diffraction loads, while its radio antenna is torn off and the vehicle rolled over by drag loads.

FAE weapons, with their relatively long impulse and relatively low blast overpressure, are ideally best matched to soft targets. Aircraft, unreinforced buildings, missiles of all kinds, trucks and other unarmoured motor vehicles, radar and communications antennas, and troops are soft. Lightly armoured combat vehicles, APCs and the like, reinforced buildings, concrete bunkers, artillery, and tanks vary from intermediate to hard, and accordingly may not be suitable FAE targets. However, one should not overlook the possibility of attacking the soft sub-systems mounted on hard targets. For example, tanks and APCs could be rendered virtually useless by destroying their antennas and external stores.

Any target, hard or soft, requires a certain minimum or critical impulse and peak over-



pressure to be damaged. Once having satisfied these minimum requirements any combintion of impulse and overpressure will do the ,ob.. This information can be very conveniently presented in a P/I vulnerability diagram, as shown in Figure 3a. The curve in Figure 3a separates the vulnerable and invulnerable P/I domains for a given target. Every target has its own curve. The harder the target, the more the curve moves up and to the right, reflecting

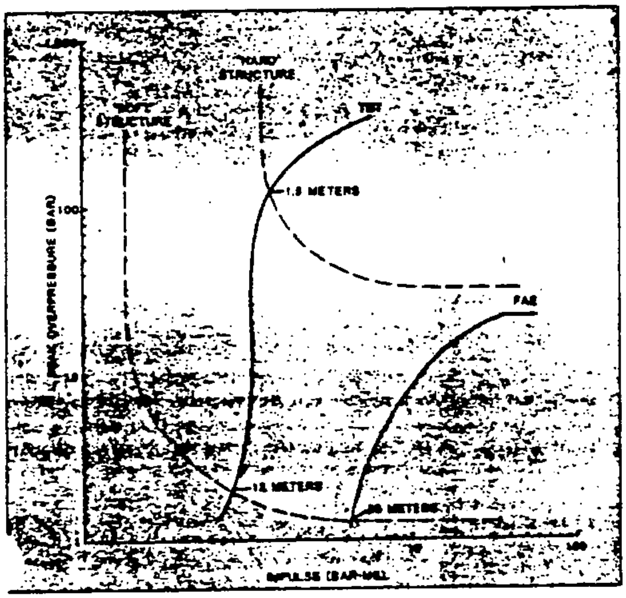
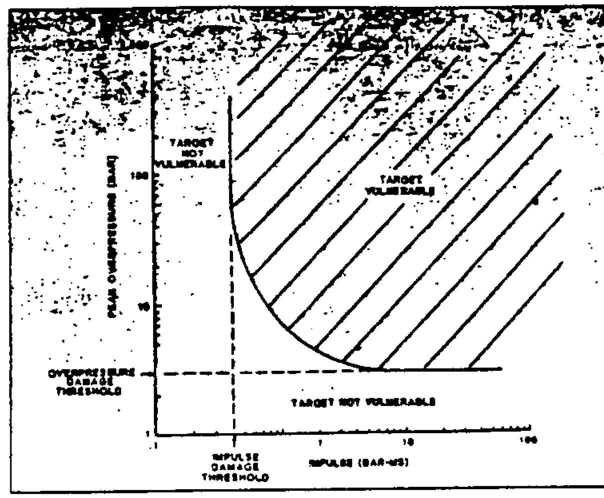


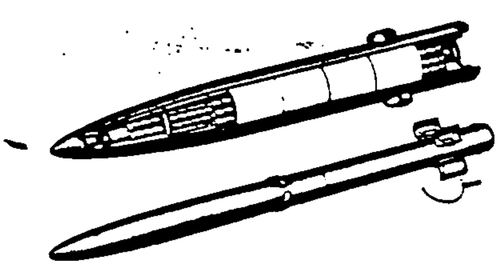
Fig. 3b: Companson of hard and soft target vulnerability to 227kg of TNT and FAE.

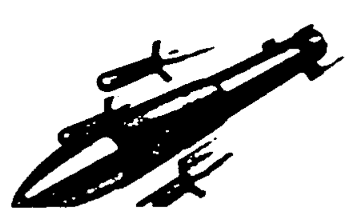
Fig. 3a: Target pressure/impulse vulnerabilivy.



greater minimum impulse and overpressure for assured destruction. It is often not practicable to calculate the curve, even with a large computer, although it can be computed for some simple systems. The curve is more frequently defined by a combination of expenmental and computational techniques.

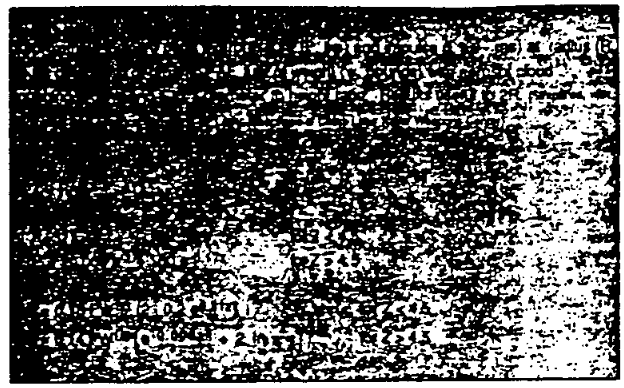
Figure 3a represents a hypothetical soft structure vulnerability. Figure 3b shows the P/I curves for hypothetical soft and hard structures together with a plot of P and I as a function of blast radius for 227 kilograms of TNT and 227 kilograms of a typical FAE fuel. Figure 3b instantly shows the advantages and limi-





lations of FAE over conventional high explosives. FAE will not destroy the hard structure since the FAE curve and hard structure curve do not intersect. Moreover, increasing the amount of FAE fuel will not help since that merely extends the FAE curve to the right (peak overpressure for an FAE fuel is independent of the quantity of fuel). On the other hand, the FAE and soft structure curves inersect at 30 metres on the FAE curve. This is the lethal radius for this FAE weapon. Compare this to the 12-metre intersection point on the TNT curve. Clearly the lethal radius against this soft structure for 227 kilograms of FAE exceeds that of an equal quantity of TNT by two and a half times.

Table III: FAE blast computation.



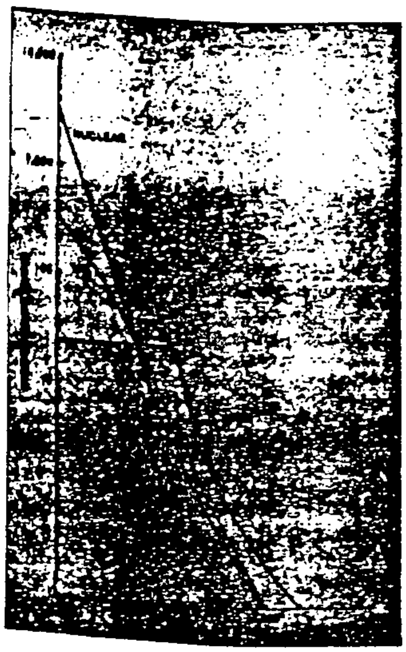


Fig. 4a: Overpressure for 1KT nuclear, TNT, FAE.

Fig. 4b: Impulse for 1KT nuclear, TNT, FAE.

A comparison of overpressure and impulse versus distance for equivalent/equal masses of nuclear, TNT, and FAE explosives immediately reveals the advantages and limitations of FAE weapons (Figure 4a, b). The peak overpressures available in the near field from FAE are substantially less than those of TNT and nuclear weapons. This significantly limits the effectiveness of FAE against hard targets. On the other hand, Figure 4b shows that the FAE impulse is about a hundred times greater than TNT. This gives FAE a much greater effectiveness against soft targets. It is also appropriate here to point out that FAE is not a substitute for nuclear weapons as has sometimes been reported in the literature. It might be used on a small scale to simulate nuclear weapons effects for vulnerability testing, but the quantity of FAE fuel needed to substitute for a tactical nuclear weapon of even fractional kiloton yield does not suggest a very practical device. An FAE weapon with a yield equivalent to a 0.1 kiloton nuclear weapon would weigh 45,000 kilograms and have a volume of 52 cubic metres.

The weaponisation of FAE is dominated by the challenges of creating the proper fuel air mixture and then detonating it at the correct time. A generic FAE bomb (Figure 5) might be a right circular cylinder, two or three diameters long, filled with fuel and fuzed to burst open at a suitable distance above the ground. A burster charge of high explosive, weighing 1 or 2% of the fuel weight, is located in a tube along the bomb's central axis. The purpose of the burster charge is to break open the container and distribute the fuel in a cloud such that the volume of air filled will contain sufficient oxygen for complete fuel oxidization. This volume is determined by the quantity and reaction chemistry of fuel (Figure 1). When the fuel is a liquid the burster charge also serves the purpose of shattering the liquid into a micromist aerosol so that it can be detonated. This is an extremely important and delicate function since the detonability of the fuel is determined, in part, by the aerosol droplet size.

The aerosol is detonated once the cloud reaches the diameter for the optimum fuel-air ratio (also kown as the stoichiometric ratio). The "second event" detonator, like the burster charge, is also a high explosive weighing a few percent of the fuel weight. The reason the burster charge doesn't detonate the fuel while the detonator does, is that the fuel is not in a detonable aerosol form at the "first event." The detonator is ejected from the generic bomb shortly before the burster charge goes off. It is slowed with a suitable drag device so that it enters the aerosol cloud and detonates at the instant of fuel-air stoichiometry. An FAE weapon would be considerably more simple if this obviously very tricky procedure could be avoided by finding some way to get the fuel to self detonate the instant it reaches stoichiometry.

The effects of weather on FAE cloud formation and detonation are not very well known. Apart from some anecdotal data it has been established that temperature and humidity can change the required detonation energy by as much as 10 or 20 %.

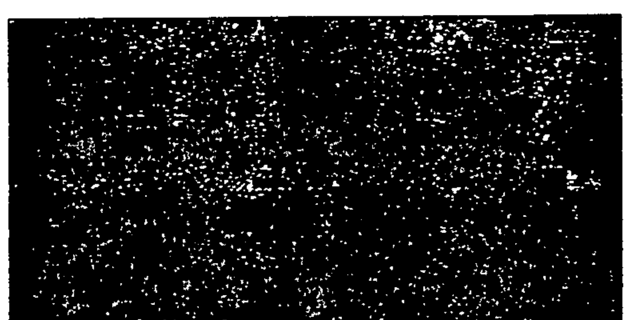


Fig. 5: Generic FAE bomb.

Safety is an important issue in weaponising FAE. Some fuels, such as aluminum powder, are benign, while others may be corrosive, unstable, inflammable, explosive, or toxic. Table V lists a few of these factors for some selected fuels. Sometimes a fuel can be selected to reduce some of these hazards. For example, the high volatility of ethylene oxide makes it difficult to contain safely at elevated temperatures. Propylene oxide is, nevertheless, a somewhat difficult material to handle and store, and could pose a fire hazard if the container leaked. Indeed, liquid fuels, in general,

Item	Diffraction	[illegible]	Hard or Soft	Suitable Explosive
[illegible]	X	[illegible]	H	HE
Reinforced Bldg.	X	[illegible]	H	HE
APC	X	[illegible]	H/S	HE
SP Howitzer	X		H/S	HE
Bridge		X	H/S	HE/FAE
Missile	X	X	S	FAE
Aircraft	X	X	S	FAE
Troops	X	X	S	FAE
Antennae		X	S	FAE
Motor Vehicles	X	X	S	FAE
Unreinforced Buildings	X	X	S	FAE

HE = High Explosive
FAE = Fuel-Air Explosive

Table IV: Hard and soft targets, blast couplings, and blast sources.

are often looked upon as more hazardous than solids because of potential leakage problems. Geling the liquid is one potential method of dealing with this difficulty that is currently being investigated.

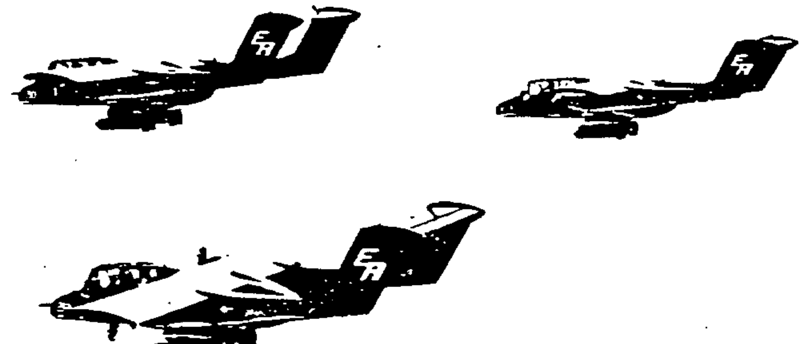
The weaponisation of FAEs is also some- ·es controlled by the selection of the delivery :ainer. If the container is already deter- ‹ed, for example, the weapon must be contained in a standard 226 kg (500 pound) bomb assembly, or in a 155mm artillery shell, then the quantity of fuel may be either weight or volume limited. Such constraints can give added importance to high-density fuels.

The only US FAE weapon ever fielded in battle in significant numbers was the BLU-73/B containing 33 kg (72 pounds) of ethylene oxide. It was used by the navy in Vietnam in the CBU-55/B cluster bomb. The CATFAE minefield clearing system is currently in development, but it is still several years from production. Other FAE weapons have been developed with varying success, but none have been deployed. These include the FAESHED, MADFAE, SLUFAE, HFS-I, HFS-II, BLU-95/B, and BLU-96/B. Elsewhere in the West there seems to be little interest in developing FAE weapons with no non-US programmes known to the author, except for the Canadian FALLON FAE line charge mine-clearing system. Persistent reports of Soviet FAE weapons development and use appear to be conjecture based on hearsay or anecdotal evidence, or extrapolations from normal Soviet activities in chemistry and explosive dynamics.

Table V: Safety issues for some FAE fuels.

[illegible]	[illegible]	[illegible]	Explosive	Toxic
[illegible]	No	[illegible]	No	No
[illegible]	No	Yes	[illegible]	No
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

OV-10A BRONCO, carrying three CBU-55/B FAE cluster bombs.



The FAE "gap" sometimes alluded to is probably more a worse case fear than a hard reality. In any event, the designation of Soviet or Westen FAE weapons as "second generation" or "third generation" considerably inflates the hard reality which better suggests the existence of a "1-1/2" generation at best.

Deployment and Use

FAE weapons development has been somewhat erratic over the years. Some of this has originated from misunderstandings of the FAE phenomena, some from the difficult weaponisation problem which to some degree remains yet unsolved, and some to the West's fixation on Soviet tanks, the hardest of hard targets. FAE, of course, is not well matched against hard targets. On the other hand, there is now sufficient knowledge and experience to successfully get on with the weaponisation. As for Soviet tanks, the tactician would surely acknowledge that there are additional targets on the battlefield of comparabe importance that are ideal soft targets for FAE. For example, the loss of battalion C^3I assets could effect the battle as much as the loss of all the unit's tanks. Moreover, the global political picture is slowly changing. A study done by the International Institute for Strategic Studies has suggested that future combat is much more likely to occur where hard, armoured targets will be infrequent, but where soft targets will be the rule.

FAE weapons are sufficiently novel that the implications of their existence should be examined. FAE fuel clouds envelop targeted areas. Accordingly, the FAE projectile need not make a direct hit on the target to be effective. For example, a riveted aircraft would be unharmed if a 227 kg HE bomb exploded five metres away on the other side of the revetment. A 227 kg FAE weapon set off at the same distance would create a ten-metre radius aerosol cloud enveloping part of the revetment and the enclosed aircraft which would be severely damaged by the detonation. This means that the CEP and guidance requirements for FAE delivery systems could be considerably eased. The cost consequences of such reduced requirements could be significant.

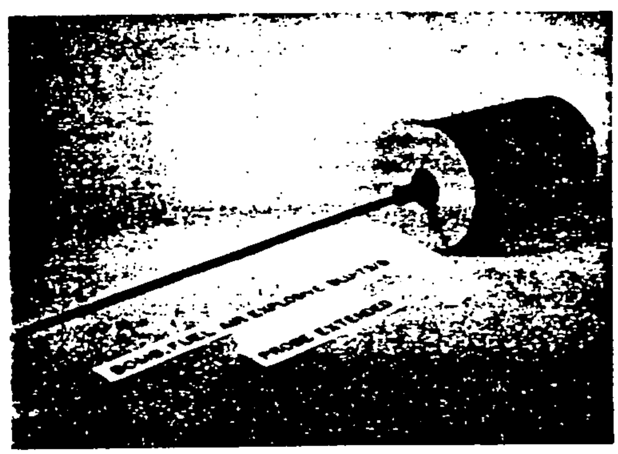
CATFAE, a mobile minefield clearing system with 21 catapult-launched rounds, each containing 63 kg (139 pounds) of FAE fuel, will penetrate conventional minefields with such ease and speed that it brings into question all future tactics that rely on conventional mine barriers. Moreover, the CATFAE rounds would be highly effective against dismounted infantry in dug-in squad and platoon positions. Foxholes and buildings provide very little protection against an enveloping FAE cloud and its blast effects. A single round could have a lethal radius of ten metres or more.

FAE as a demolition mine-clearing weapon was used in Vietnam to prepare helicopter landing sites in the jungle by clearing foliage and mines. FAE weapons used in this manner give additional flexibility to helicopter operations.

This form of explosive could become the most frequent weapon of choice in future conflicts, because it is primarily a soft-target weapons. Recent history suggests that the era of big power wars may have ended. While nuclear powers dare not attack each other, smaller nations continue manoeuvring for advantage vis-a-vis their neighbours and the larger powers. Conflict in such a context is more likely to present soft rather than hard targets. It is important to understand, however, that the essential area weapon characteristic of FAE gives one relativley little capacity to discriminate between targets and, therefore, precludes its efficacy in operations directly among civil populations.

The future of FAE and its weaponisation will depend very much on its assessed utility as a total system within the combat requirements of the West. It has potential in the classical combat context or any combat where there are identifiable soft targets. The most productive future developmental efforts will probably be in the direction of weaponisation and the creation of self-detonating fuels.

The BLU-73/B FAE bomblet (right) contains 33kg of ethylene oxide. Three BLU-73/Bs are accommodated inside the CBU-55/B cluster bomb (below), the only FAE weapon ever used in battle in significant numbers.



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Added Richard E. Donnelly, who [illegible]tly served as acting deputy assistant secretary of defense for pro[illegible]ion: "National security comes in many flavors. It just isn't men and women, ships, aircraft and tanks; it's the ability of our industrial infrastructure to supply."

Apart from the sheer size and speed of the military buildup in the gulf, the desert environment in which it is taking place has put extraordinary demands on the supply system. "It's kind of like you packed to go on vacation in Alaska and you ended up in Hawaii," said Donna M. Heivilin, director of logistics issues for the General Accounting Office.

Clothing manufacturers have been ordered to switch from the traditional woodland green combat fatigue to a lighter, desert tan version. The steel plates that lined the soles of combat boots, designed as protection against sharp punji stakes in Vietnam, have been removed because they were unnecessary and got hot, officials said. Special care has been taken to provide food products capable of withstanding extreme desert heat.

Operation Desert Shield's effect is being felt in places such as Beloit, Wis., and Plainview, Minn., both locations of Geo. A. Hormel & Co. [illegible] that are working overtime to [illegible]44.6 million order for micro[illegible]able entrees of pot roast, lasagna and other food items.

The pace got so intense last month that Hormel told some commercial customers certain promised orders were being diverted to the Pentagon. Some, like Giant Food in [illegible]ndover, did not object, but other [illegible]ms—including a large food [illegible]ain—were unsympathetic.

"Let's put it this way: it strained [illegible]r relationship with some of our [illegible]portant accounts," said Eric [illegible]rown, a Hormel vice president.

In dozens of apparel factories in the rural south, uniforms are being produced and jobs have been created at a time when economic prospects seemed bleak.

In Mayaguez, Puerto Rico, a clothing and flak jacket manufacturer contacted the local unemployment office to help find 250 workers after receiving an $11.4 million Desert Shield contract.

In Brooklyn, N.Y., the Isratex line of chemical warfare protection suits suddenly has a new market. And inside the Bastrop, Tex., federal prison, 110 inmates are being [illegible] approximately 88 cents an [illegible] to rivet bullet-resistant hel-[illegible]

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MINNEAPOLIS STAR-TRIBUNE Dec. 16, 1990 Pg. 19

Possible Honeywell data sale to Iraq probed

By Sally Apgar
Staff Writer

Pentagon investigators are questioning Honeywell executives about the possibility that plans for a sophisticated missile guidance system were sold to Iraq through a Swiss arms broker.

Weapons experts said that the possibility of Iraq possessing plans for the Honeywell guidance system could be more worrisome than Honeywell's recently reported sale of a 300-page technical study on a powerful bomb to the same Swiss arms broker. The guidance system could give any missile a deadly precision.

It is not known whether the Honeywell guidance technology is in the hands of the Iraqis, who have been scavenging technology from Western defense companies for at least six years, according to defense experts.

Two weeks ago, it was reported that Honeywell sold a study on a bomb, called a fuel-air explosive, to Iraq for $100,000 through IFAT, a Swiss company working for Argentina, Egypt and Iraq.

The 1984 sale is being examined by the Pentagon and Honeywell investigators from Covington & Burling, a Washington, D.C., law firm hired after the sale was made public.

Pentagon sources said last week that they are questioning Honeywell to determine whether one of its executives sold plans for a ring laser gyroscope to IFAT in 1984. The device is considered the heart of Honeywell guidance systems and is manufactured at its plant on Stinson Blvd. in northeast Minneapolis.

The device, which employs a system of lasers and mirrors, can be used to guide commercial or military aircraft as well as missiles. Weapons experts speculate that the Iraqis would use the technology to make guidance systems for missiles loaded with either chemical weapons or explosives such as the fuel-air explosive.

Intelligence sources believe the Iraqis are at least a year from building a nuclear bomb.

Honeywell acknowledged that investigators from the Defense Technology Security Administration met with company officials Tuesday to discuss the bomb study and other possible sales to IFAT. Pentagon officials asked the company to look for documents that would indicate whether plans for the ring laser gyroscope were sold to IFAT.

"We have not been able to find any information to support that inertial guidance technology was transferred to IFAT," Honeywell spokeswoman Susan Eich said Friday.

Clyde Bryant, chief of compliance for the State Department's Office of Defense Trade Control, said that fuel-air explosive and ring laser gyroscope technologies are "tightly controlled."

At the time of the alleged sales, Bryant said, the two technologies were on the State Department's munitions list and would have required permission and an export license from the government. Those licenses are not public.

Honeywell came under Pentagon scrutiny along with other U.S. defense contractors after five senators wrote a letter to Secretary of Defense Dick Cheney in September. They requested a Pentagon investigation to determine whether American companies sold military technology to Iraq that could be used against U.S. troops in the Persian Gulf.

Specifically, the letter questioned how fuel-air technology got into Iraqi hands. Subsequently, Honeywell was drawn into the review by reports of the bomb study sale.

The bomb, which Honeywell developed for use in Vietnam, detonates in two stages. The first disperses an aerosol cloud of fuel over a large area and the second ignites the vapor into a deadly burning cloud. Weapons experts say that within an area the size of three football fields, the bomb can flip planes or boats, demolish buildings or bunkers and kill people by fire or concussion.

"We're looking into everything and anything Honeywell may have done transferring technology to Iraq," Defense Department spokesman Rick Oborn said last week.

Intelligence experts say that during the 1980s, Iraq became increasingly resourceful at procuring different technologies and weapons materials from the West by using several front companies and agents.

At the heart of these companies is IFAT, which is part of Consen, a network of 16 companies based in Zug, Switzerland, and Monte Carlo, Monaco.

"Zug is a nest of techno-bandits," said William Triplett, an expert on Iraqi weapons and poison gas procurement who works for the Senate Foreign Relations Committee.

"There are more fax machines and fake banks in Zug than probably anywhere else in the world."

In their letter, the senators said that Messerschmitt-Boelkow-Blohm, Germany's largest aerospace firm, may have been most directly responsible for giving the fuel-air bomb technology to the Iraqis. They noted that the alleged transfer would have occurred during the "Egyptian-Iraqi Condor II ballistic missile project to which (Messerschmitt) was a major contractor."

In 1984, Iraq, then in a death struggle with Iran, joined forces with Egypt and Argentina to procure their own version of the U.S. Pershing missile. The Iraqis are attempting to build what is believed to be a two-stage, solid-fuel rocket with a range of 620 to 650 miles. That project, known as Condor II or Bader 2000, involved the use of companies such as IFAT as fronts.

Consen, which includes scientists and engineers from Messerschmitt and other Western defense companies, supplied technical support for the three nations as they pursued several armament projects, according to investigators.

Initially, money and technology flowed in and out of Egypt. But eventually, experts believe, the three countries split and Iraq pursued the acquisition of chemical and explosive weapons systems on its own.

As Pentagon investigators attempt to trace the flow of technology and components through this web, there is much at stake for U.S. defense contractors such as Honeywell.

The senators' letter says that "should the (Pentagon's) investigation determine that any U.S. or foreign firms are culpable, contract debarment procedures would be initiated immediately."

Government officials say it appears that the bomb study did not violate regulations governing the export of military technology because it was written in a general manner. The bibliography of the study cites more than 150 public sources.

Honeywell said last week that its initial investigation also showed that the study consists "of already published, unclassified information in the public domain. Such generic information, readily available to anyone who wanted it, would by itself be far from sufficient to design or build an FAE weapon."

Honeywell said that it has encouraged employees to come forward confidentially or to use the company's ethics hot line if they have information that will aid the investigation.

Michael Butler, a Washington attorney who works on many export licensing cases, said the penalties for violating export laws are so severe that companies are extremely careful.

"There's lethal language in the regulations that basically says companies can be barred from exporting anything," he said. "A big company just can't afford to get involved in this kind of thing."

GIs...from Pg. 14

"So his numbers should not be a problem," he concluded. "With our mass and our technology, it should be a pushover."

So say the model-builders. But skeptics remain unconvinced.

"Models and modern analysis can do lots of things," one experienced former officer said. "But they are not good at prediction, at telling you how fast you'll move, how long the war will take, how many men you'll lose."

SUPPLIED...from Pg. 17

Perhaps the most critical supplier in the days immediately after the August decision to deploy U.S. troops to the gulf was an ancient clothing factory in a busy neighborhood in South Philadelphia. The only such factory owned by the Defense Department, the plant once outfitted soldiers in the Civil War. Now, 1,500 uniforms, 700 hats and 700 canteen covers are being churned out daily by 1,500 civilian employees.

One worker, Ella Abner, 68, started at the plant 48 years ago. She remembers operating a sewing machine during World War II, in which her brother fought. She bundled uniforms during the war in Vietnam, where her son served. Now she removes spots from new desert fatigues and writes to Emmett Abner, her 20-year-old grandson, a Marine in the gulf.

Elsewhere in the sprawling complex, which includes offices of the Defense Personnel Support Center, officials are cutting red tape to make the necessary deals to meet the Pentagon's urgent timetable. "Paperwork to follow" is the byword of the hour. Where once it took up to six months to consummate a military contract, huge deals now are arranged in just a few days.

For example, Wrangler, the jeans maker, had not done defense work since the days of the Vietnam War. On Oct. 2, it was contacted by the Defense Logistics Agency, and on Oct. 17, it had a sole-source, $17.2 million contract to produce 1 million pairs of battle fatigues. The first ones came off the line Tuesday.

The chief commercial beneficiaries of Desert Shield appear to be specialized companies—the makers of uniforms, producers of boots, assemblers of food packages and manufacturers of everything from chigger repellant to sunglasses to nerve gas antidote.

Paradoxically, the huge contractors that provide the Pentagon with its most sophisticated and expensive systems have so far benefited less, experts said.

"The performance of the supply system of Desert Shield has nothing to do with the ability of the [defense] industry to react to a crisis," said James Blackwell, a senior fellow at Center for Strategic and International Studies, who studies defense industrial issues. "It has everything to do with the fact that people in the supply business were able to take things off the shelves and move them down to Saudi Arabia," thanks in large part to surpluses resulting from the Pentagon's huge acquisitions programs of the 1980s.

"I think the system's basically living off of what was already in the pipeline," said Norman R. Augustine, chairman and CEO of Martin Marietta Corp., and a former undersecretary of the Army. "There's been very little impact on the industry as a whole, and certainly that's true of our company."

Augustine said several of his firm's systems are part of the Desert Shield operation—such as Hellfire laser-guided missiles for Army attack helicopters and the LANTIRN nighttime navigational system for Air Force fighters—but the production of only one set of items—portions of the Patriot missile made for Raytheon—has been accelerated.

Although many defense experts said Operation Desert Shield offers no promise of reversing planned reductions in future defense budgets, some bigger firms may still benefit from the proposed $20 billion Saudi arms package and other arms deals involving Middle Eastern countries.

Meanwhile, hundreds of firms around the United States continue to manage the day-to-day problems of keeping alive the supply lines to the gulf. •

In Vineland, N.J., National Freight, on call seven days a week for the Defense Logistics Agency, is one of several firms with contracts to haul supplies from manufacturers to military depots in places such as Memphis and Richmond. The burst in business has enlivened an otherwise slow holiday season. "I don't want to see us go to war," said Jeff Brown, vice president for sales and marketing, "but it certainly fit in. . . . The government came at a real nice time."

In Lincoln, Neb., Calvin Fisher, owner of Fisher Foods and an inventor of "spray-dried," just-add-water scrambled eggs, said a new $14 million Desert Shield contract for his "Ready Egg" is triple his normal annual military sales, and he suspects the troops will soon need more of his product.

"For cripes sake," he said of the soldiers stationed in the desert, "they've got them cooped up, they can't go anyplace and they're eating like crazy."

The three firms that produce MREs—the dehydrated Meals Ready-to-Eat that constitute a main source of nourishment for U.S. troops in the desert—were expecting cutbacks in Defense Department purchases of nearly 30 percent this year. But sales soared after the gulf deployment began, fro[m] 2¼ million cases annually, to [?] million cases per month, said T[?] Bevels, the industry's Washingt[on] representative. "We can barely keep up with the demand."

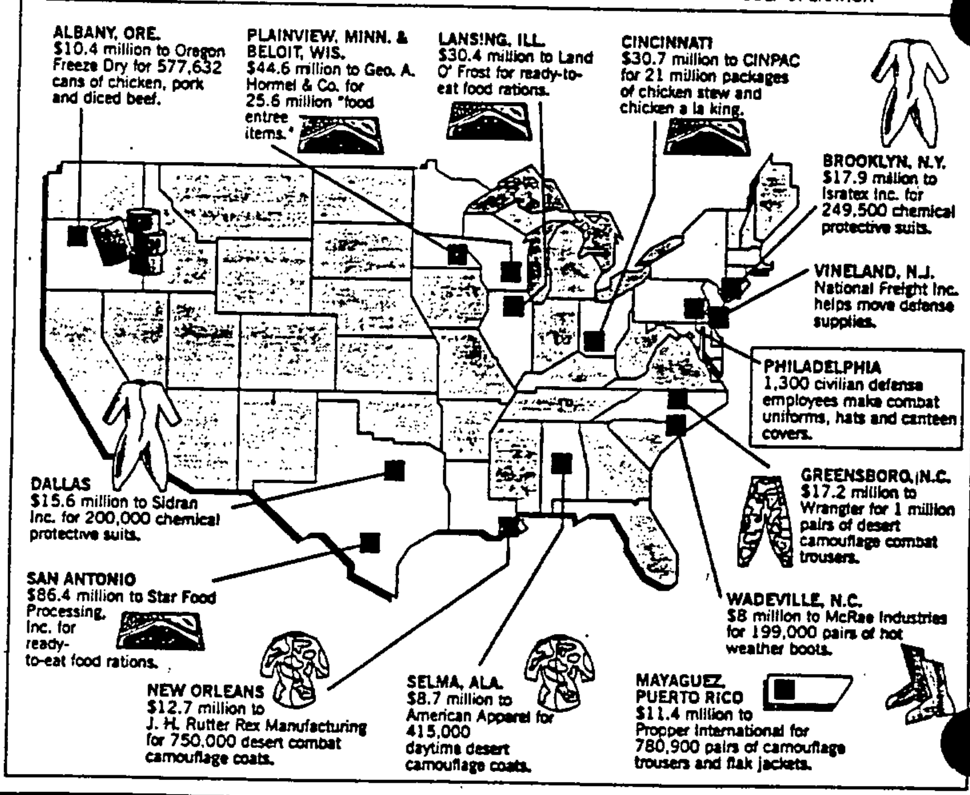
Wrangler's contract with the Pentagon may pay off in more ways than one. After it was announced, the firm was deluged with calls, said Bill Koronis, a company official. An upscale mail-order house wanted a line of camouflage trousers. A national retailer asked for camouflage childrens' shorts. Several Saudis called from Riyadh, Saudi Arabia, requesting a private deal with the firm.

The news is also good for Wadeville, N.C., where McRae's big layoff had a severe impact in the community of 1,000. It could have all been avoided, said McRae, who said he warned defense logistics officials last year that their decision to stop purchasing combat boots was unwise.

"We had a meeting with them. We told them, 'Look, you've got to keep us alive. You don't know when a war will break out. . . . We've always had a war sooner or later.' "

THE RUSH TO SUPPLY DESERT SHIELD

SELECTED DEFENSE CONTRACTS AWARDED IN CONNECTION WITH PERSIAN GULF OPERATION



Honeywell says bomb data sale violated policy

By Tom Hamburger and Sally Apgar
Staff Writers

Employees at Honeywell Inc. violated company policy by selling a report on fuel-air explosives (FAE) bombs to a Swiss firm acting on behalf of other foreign countries, an internal Honeywell investigation has found.

But the 1984 sale was made in good faith and without intent to violate the law, the report said. The company concluded that the sale of the non-classified document required no disciplinary action.

"It was a mistake," said Honeywell Chairman James Renier in an interview Thursday. " ... Clearly, some people assumed that since this report was not classified it was all right to go ahead."

He said company policy dictates that every document coming out of Honeywell, including technical articles for scientific journals, must go through an approval process.

"My frustration is that it went around standard procedure," he said. "It absolutely is an anomaly."

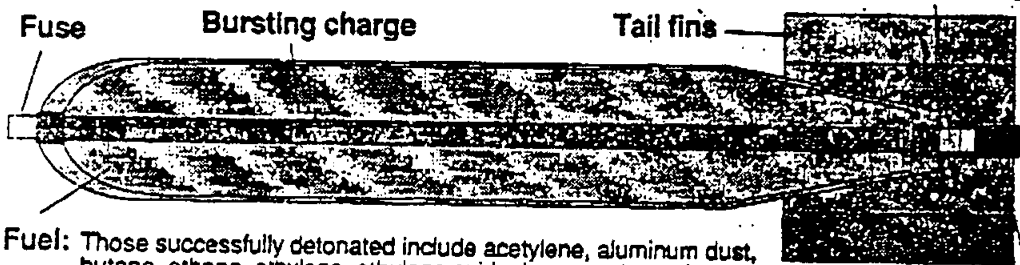
Honeywell's two-month investigation was sparked by news reports that Iraq had acquired a description of the company's FAE technology by using "front" companies in Europe. Honeywell said it thought that the FAE study was ultimately destined for Egypt, and had no knowledge of Iraqi involvement.

Honeywell provided its findings to Defense Department investigators

Bomb continued on page 16A

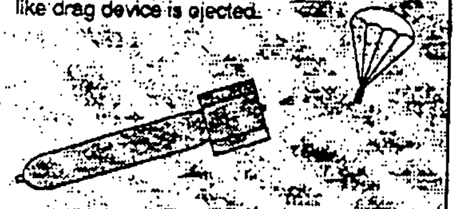
Fuel-air explosives

As their name implies, fuel-air explosives detonate after the fuel they contain mixes with the oxygen in the air. They can be delivered to a target by the same methods as conventional high explosives. High explosives such as TNT can destroy hardened targets such as tanks and buried bunkers but the force of their shock waves does not carry as far as that of the FAE bomb. In addition, the cloud of fuel that precedes the FAE blast can penetrate structures before exploding.

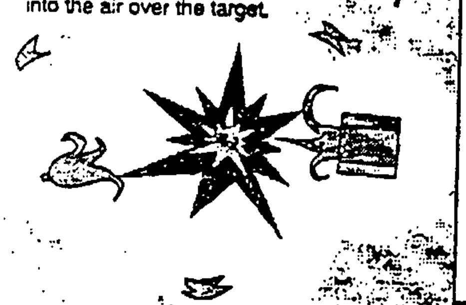


Fuel: Those successfully detonated include acetylene, aluminum dust, butane, ethane, ethylene, ethylene oxide, heptane, kerosene, methane, propane, proplyene, propylene oxide.

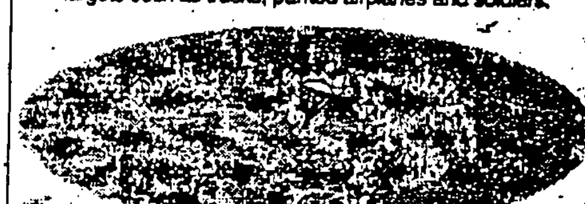
1 At a suitable distance above the ground the fuel-air cloud detonator and its parachute-like drag device is ejected.



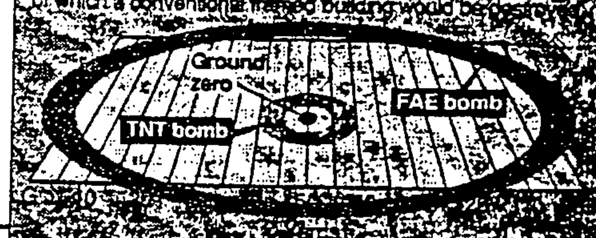
2 Seconds later, the bursting charge explodes, rupturing the bomb casing and rapidly dispersing a cloud of fuel into the air over the target.



3 When the fuel and air are mixed at the proper ratio in the expanding cloud, the detonator fires, causing the cloud to explode. The resulting blast is devastating to unarmored targets such as trucks, parked airplanes and soldiers.



Below is a comparison of the destructive power of a 500-pound FAE bomb using kerosene for fuel and a conventional high explosive TNT bomb of the same weight. The fuel cloud of the FAE bomb is 70 feet in diameter when it is detonated. The bombs are exploded in the middle of a football field for size reference. The toned rings indicate the distance inside of which a conventional framed building would be destroyed.



Source: Louis Lavoie

Star Tribune graphic/David Silk

Bomb Continued from page 1A

earlier this week and will be used in the department's continuing probe of Iraqi weapons transfers.

The FAE bomb, developed in the 1960s, is especially valued in desert warfare. It disperses an aerosol cloud of fuel over a large area, then ignites the vapor. The resulting blast can

for Israel.

Honeywell provided the Star Tribune a four-page executive summary of its investigation conducted by the Washington, D.C., law firm of Covington & Burling. Honeywell declined to identify employees involved in the sale, including those

senior executives approved the deal. However, minutes of a mid-level staff meeting indicated senior-level approval before the FAE report was written, he said.

The two-part report concluded that there was no evidence of any military sales directly or indirectly to Iraq.

But Pentagon and U.S. Customs in-

... wide areas, crash bunkers, rip airplanes or boats, and kill either by fire or concussion. The bomb is considered so destructive that the United States has denied export licenses

who approved it.

Coleman Hicks, the investigating attorney for Covington & Burling, said there was no documentary proof that

... looking at transfers of technology to Iraq believe that Iraq built its arsenal during the 1980s by just such a route, scavenging technol-

Bomb continued on page 17A

Bomb Continued from page 16A

ogy from around the world through a variety of front companies, including the one that bought the FAE description from Honeywell.

When the Honeywell deal was made in 1984, employees thought they were selling to a Swiss firm acting on behalf of the Egyptian military.

But some Honeywell engineers on the project repeatedly objected to the sale because of concerns about the potential customer. "It just seemed to me that the Mideast is so volatile that it was not a good idea" to sell to Egypt, said Louis Lavoie of Plymouth, the Honeywell engineer who wrote the study.

At the time, Egypt was a U.S. ally, but remained on a State Department's restricted-munitions list, which required government review of military sales. Honeywell also placed Egypt — along with Iraq — on a restricted list in 1984.

"I think the proposition is immoral," Honeywell's John Beckmann wrote to superiors in an April 1984 memo obtained by the Star Tribune. "It violates Honeywell principles and is not in the best interests of Honeywell," he wrote.

The second investigation, conducted over the past two months by Alliant Techsystems Inc., the company created last year when Honeywell spun off its defense businesses, concluded that no classified material was contained in the 300-page report passed to the Institute for Advanced Technology (IFAT) in Zug, Switzerland.

IFAT has been described as a front company set up by Iraq, Egypt and Argentina to acquire missile technology. Eventually, however, Egypt and Argentina left the company under Iraq's control.

The law firm's review cited experts who concluded that Honeywell's FAE study was of little military value and could not have helped Iraq develop FAE capability. The Honeywell report found "no evidence of any direct transfer" to suspected FAE suppliers to Iraq.

But the Honeywell report conflicts with accounts provided by the German magazine Der Spiegel, linking the Honeywell FAE documents to Iraq. Der Spiegel reported that FAE technology description was transferred from Honeywell to IFAT, to the German defense manufacturer Messerschmidt Bolkow-Blohm (MBB), which, in turn, passed the technology on to Iraq. MBB has denied involvement in the arms transfer.

But Iraq displayed its own version of an FAE weapon in Baghdad in 1989, according to Kenneth Timmerman, a Paris-based defense analyst.

Hicks confirmed that Smith's introduction to Honeywell was smoothed by Gareth Thornton, who was a supervisor at the Honeywell's English subsidiary. The two met Smith when the two worked at Hunting Engineering, and Thornton later went to work with Smith at Charter Aerospace Ltd. in England.

As Honeywell officials understood it, IFAT was representing the Egyptian government. Several Honeywell employees in Minneapolis, including Beckmann and Lavoie, were suspicious of Smith and IFAT. In several memos, they urged superiors not to sell.

The summary did not address what happened to the memos and who made the decisions to proceed despite the objections.

Hicks said that it is unclear whether senior managers with approval authority actually signed off on the project.

In England, Hicks found that Honeywell's former subsidiary had been sold and that documents before 1989 had been destroyed. In Minneapolis, he found that some documents were destroyed as part of Honeywell's standard routine of disposing of certain documents after five years.

Hicks did find the minutes of a meeting in which the FAE study was discussed. From those notes, he said, individuals at the meeting felt that the project had the proper approval.

"But no one has a recollection of approval and there are no documents showing it," said Hicks.

Hicks interviewed executives who would have had the authority to approve the project and found that after seven years, they did not recall anything.

Honeywell reported that it found no evidence of any transfer by the company, directly or indirectly, of any technology regarding ring laser gyroscopes, cluster bombs or fuses, either to Iraq or any intermediary. A ring laser gyro is a sophisticated guidance system used in aircraft and missiles.

scopes, cluster bombs or fuses, either to Iraq or any intermediary. A ring laser gyro is a sophisticated guidance system used in aircraft and missiles.

Defense investigators in Washington, Madrid and Bonn have been working to determine how the weapon made its way there. Honeywell has voluntarily provided its entire report to Pentagon investigators.

The FAE project was first proposed by IFAT to a two-year-old Honeywell subsidiary in Bracknell England in 1984. IFAT, Renier and Coleman Hicks said the desire to find new business may have driven the sale of the FAE study. According to Hicks and internal documents, IFAT representative Keith Smith approached the English subsidiary in 1984, requesting a technical study.

...e from a street in old Beirut's downtown this

Investigators are questioning Honeywell about the possibility that plans for a missile guidance system were sold to Iraq. But analysts say the alleged incident is simply one of many technology transfers during the 1980s.

U.S. helped Iraq build technology for its arms

By Tom Hamburger
Washington Bureau Correspondent

Washington, D.C.
If it comes to war against Iraq, the United States will engage its most sophisticated military foe since World War II. And some U.S. companies and policymakers will have themselves to blame.

Iraq's advanced military capability could not have been built without foreign support, much of it from the United States. This support — in weapons, technical information and training — was not always provided surreptitious or illegally. It often was provided over the objection of Pentagon officials. It sometimes went with the blessing of the National Security Council.

"Limiting the flow to Iraq was extremely frustrating," said Stephen Bryen, former deputy undersecretary of defense for trade security during the Reagan administration. "Even the things we did see as problems ran into a great deal of pressure — pressure to release things to Iraq. We'd point out that a certain product can be used for missiles and we'd end up in big arguments with (the Departments of) State and Commerce."

President Bush has railed against the barbarism of Saddam Hussein since Aug. 2. But for seven years before Iraq's invasion of Kuwait, the Reagan and Bush administrations relaxed export restrictions to Iraq to help keep Iran in check.

Minnesota-based Honeywell Inc. recently was implicated in the possible

Possible Honeywell data sale to Iraq probed

By Sally Apgar
Staff Writer

Pentagon investigators are questioning Honeywell executives about the possibility that plans for a sophisticated missile guidance system were sold to Iraq through a Swiss arms broker.

Weapons experts said that the possibility of Iraq possessing plans for the Honeywell guidance system could be more worrisome than Honeywell's recently reported sale of a 300-page technical study on a powerful bomb to the same Swiss arms broker. The guidance system could give any missile a deadly precision.

It is not known whether the Honeywell guidance technology is in the hands of the Iraqis, who have been scavenging technology from Western defense companies for at least six years, according to defense experts.

Two weeks ago, it was reported that Honeywell sold a study on a bomb, called a fuel-air explosive, to Iraq for $100,000 through IFAT, a Swiss company working for Argentina, Egypt and Iraq.

The 1984 sale is being examined by the Pentagon and Honeywell investigators from Covington & Burling, a Washington, D.C., law firm hired after the sale was made public.

Pentagon sources said last week that they are questioning Honeywell to determine whether one of its executives sold plans for a ring laser gyroscope to IFAT in 1984. The device is considered the heart of Honeywell

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guidance systems and is manufactured at its plant on Stinson Blvd. in northeast Minneapolis.

The device, which employs a system of lasers and mirrors, can be used to guide commercial or military aircraft as well as missiles. Weapons experts speculate that the Iraqis would use the technology to make guidance systems for missiles loaded with either chemical weapons or explosives such as the fuel-air explosive.

Intelligence sources believe the Iraqis are at least a year from building a nuclear bomb.

Honeywell acknowledged that investigators from the Defense Technology Security Administration met with company officials Tuesday to discuss the bomb study and other possible sales to IFAT. Pentagon officials asked the company to look for documents that would indicate whether plans for the ring laser gyroscope were sold to IFAT.

"We have not been able to find any information to support that inertial guidance technology was transferred to IFAT," Honeywell spokeswoman Susan Eich said Friday.

Clyde Bryant, chief of compliance for the State Department's Office of Defense Trade Control, said that fuel-air explosive and ring laser gyroscope technologies are "tightly controlled."

At the time of the alleged sales, Bryant said, the two technologies were on the State Department's munitions list and would have required permission and an export license from the government. Those licenses are not public.

Honeywell came under Pentagon scrutiny along with other U.S. defense contractors after five senators wrote a letter to Secretary of Defense Dick Cheney in September. They requested a Pentagon investigation to determine whether American companies sold military technology to Iraq that could be used against U.S. troops in the Persian Gulf.

Specifically, the letter questioned how fuel-air technology got into Iraqi hands. Subsequently, Honeywell was drawn into the review by reports of the bomb study sale.

The bomb, which Honeywell developed for use in Vietnam, detonates in two stages. The first disperses an aerosol cloud of fuel over a large area and the second ignites the vapor into a deadly burning cloud. Weapons experts say that within an area the size of three football fields, the bomb can flip planes or boats, demolish buildings or bunkers and kill people by fire or concussion.

"There are more fax machines and fake banks in Zug than probably anywhere else in the world."

In their letter, the senators said that Messerschmitt-Boelkow-Blohm, Germany's largest aerospace firm, may have been most directly responsible for giving the fuel-air bomb technology to the Iraqis. They noted that the alleged transfer would have occurred during the "Egyptian-Iraqi Condor II ballistic missile project to which (Messerschmitt) was a major contractor."

In 1984, Iraq, then in a death struggle with Iran, joined forces with Egypt and Argentina to procure their own version of the U.S. Pershing missile. The Iraqis are attempting to build what is believed to be a two-stage, solid-fuel rocket with a range of 620 to 650 miles. That project, known as Condor II or Bader 2000, involved the use of companies such as IFAT as fronts.

Consen, which includes scientists and engineers from Messerschmitt and other Western defense companies, supplied technical support for the three nations as they pursued several armament projects, according to investigators.

Initially, money and technology flowed in and out of Egypt. But eventually, experts believe, the three countries split and Iraq pursued the acquisition of chemical and explosive weapons systems on its own.

As Pentagon investigators attempt to trace the flow of technology and components through this web, there is much at stake for U.S. defense contractors such as Honeywell.

The senators' letter says that "should the (Pentagon's) investigation determine that any U.S. or foreign firms are culpable, contract debarment procedures would be initiated immediately."

Government officials say it appears that the bomb study did not violate regulations governing the export of military technology because it was written in a general manner. The bibliography of the study cites more than 150 public sources.

Honeywell said last week that its initial investigation also showed that the study consists "of already published, unclassified information in the public domain. Such generic information, readily available to anyone who wanted it, would by itself be far from sufficient to design or build an FAE weapon."

Honeywell said that it has encouraged employees to come forward confidentially or to use the company's ethics hot line if they have inforanything which may have done transferring technology to Iraq," Defense Department spokesman Rick Oborn said last week.

Intelligence experts say that during the 1980s, Iraq became increasingly resourceful at procuring different technologies and weapons materials from the West by using several front companies and agents.

At the heart of these companies is IFAT, which is part of Consen, a network of 16 companies based in Zug, Switzerland, and Monte Carlo, Monaco.

"Zug is a nest of techno-bandits," said William Triplett, an expert on Iraqi weapons and poison gas procurement who works for the Senate Foreign Relations Committee

tion.

Michael Butler, a Washington attorney who works on many export licensing cases, said the penalties for violating export laws are so severe that companies are extremely careful.

"There's lethal language in the regulations that basically says companies can be barred from exporting anything," he said. "A big company just can't afford to get involved in this kind of thing."

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#4

A Preliminary Study for Development of a FAE Warhead
for Application to a Ballistic Missile
Mid Study Progress Report

Honeywell

Operational Analysis

AEROSPACE & DEFENCE

HONEYWELL AEROSPACE & DEFENCE - U.K.

A Preliminary Study for Development of a FAE Warhead for Application to a Ballistic Missile
Mid Study Progress Report

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SUMMARY

In August 1984 a proposal, by Honeywell Control Systems Limited, Bracknell, Berkshire, England, on behalf of the Institute For Advanced Technology, Zug, Switzerland, to consider the preliminary assessment activities concerned with the development of a fuel air explosive (FAE) warhead, was accepted. The proposal undertook to provide a status report on the work completed at the mid point of the study, which has now been reached. This paper represents the mid study progress report.

In undertaking the work, it was necessary to consider the available literature on the subject, with a view to the appreciation of both the development of any current FAE weapon systems and any research orientated work concerned with the problems of successful fuel air explosions.

In so doing, it is evident that little information is available in the open literature concerning development of FAE weapon systems. However, it does seem that considerably more discussion on the subject took place during the early 1970's than the current time. Not withstanding this, the US Government have continued to support research into the topic.

Drawing on the available literature into the research of fuel air explosions and our own expertise in this area has allowed the consideration of various fuels together with methods of dispersion and detonation. Mathematical models have been selected to assist in the measurement of fuel energy yields and blast calculations in order to recommend a FAE payload for the final report. Targets and their vulnerabilities have been identified. An area effects model for the final assessment has been developed. The system assessment program for the remainder of the study has been outlined.

Without wishing to prejudge the conclusions of the Final Report, work to-date does indicate that a FAE warhead is capable of offering a worthwhile payload for the Ballistic Missile.

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1. INTRODUCTION

1.1 BACKGROUND

In May 1984 a proposal by Honeywell Control Systems Limited (HCSL) of Bracknell, England on behalf of the Institute For Advanced Technology (IFAT) of Zug, Switzerland was made. [1]

The study proposal covered the necessary preliminary assessment activities concerned with the development of a fuel air explosive (FAE) warhead for application to a ballistic missile. The study includes activities aimed at reviewing available data on the subject, an analysis of the lethality of different FAE options and the selection of the most effective fuel type.

The proposal was accepted on 6 August 1984 and the work commenced on that date. The work is being undertaken by two Honeywell assessment groups:

a) The Operational Analysis Department (OAD) based at Bracknell, England, and

b) The Defence Systems Division (DSD) based at Minneapolis, U.S.A.

The OAD are acting as Prime Contractor in all matters concerning the study and DSD are providing effort on a sub-contractual basis.

Further specification of the proposal and the work items to be undertaken are available from Reference 1. The proposal undertook to provide a status report on the work completed at the mid point of the study.

1.2 AIM

The aim of this paper is to provide a status report on the work completed at the mid point of the study and to indicate the work necessary for the completion of the study.

1.3 SCOPE

In the remainder of this section, a note on the units used in this report is given, followed by a brief overview of fuel air explosives by way of a short introduction to the subject.

In Section 2, the result of the literature survey into the subject is given and comprises a discussion on aspects of FAE detonation and blast, followed by a review of FAE weapon systems.

In Section 3, fuels available from a petroleum refinery together with their relevant physical and chemical properties are discussed. A list of fuels is drawn up together with calculations to indicate their relative performance.

Section 4 deals with the problems associated with aerosol cloud formation. Both the primary and secondary droplet breakup are considered as well as burster charge, cloud shape and structure.

Section 5 considers different methods of aerosol cloud detonation and discusses the time delay for cloud detonation and the possibility of multiple cloud detonation.

Section 6 deals with the measurement of blast effects from explosives and discusses a range of mathematical models used for that prediction.

In Section 7, the targets to be considered for this study are identified together with a presentation on their vulnerability to blast overpressure.

Section 8 deals with the assessmnet methodolcgy to be used for the recommendation, in the final report, of the preferable FAE payload option.

Finally, in Section 9, conclusive statements are made on the progress of the study at its mid point.

1.4 UNITS

SI units have been used wherever practical and appropriate. The only exceptions are where equations are used from the literature which have other units. In such cases, we have inserted a conversion constant to adjust to SI units. Equations presented without units specified or in non-metric values are heuristic expressions not intended for computation; accordingly, the units are irrelevant. Elsewhere, CGS units have been used where appropriate to facilitate comparison to the literature. For example, density is normally given in grams per cubic centimetre and would only confuse matters by presenting it in kilograms per cubic metre. Similarly, combustion and explosion energies are given in calories per gram of fuel instead of joules per kilogram.

1.5 OVERVIEW OF FUEL AIR EXPLOSIVES (FAE)

The basic concept of fuel air explosives (FAE) involves the dispersion of fuel in air to form an explosive cloud which is then detonated. A wide variety of fuels can be used including hydrocarbon or organic gases and liquids and organic or metallic dusts. Very many instances of accidental generation of fuel air clouds and explosions have been recorded and demonstrate the destructive power of FAE. Examples include the devastation of the Nypro plant at Flixborough UK (1974) caused by the release and subsequent explosion of 36 tons of cyclohexane and the fatal accident at the water pumping station in Lancashire UK (1984) due to a build up of methane. In the latter example it is likely that deflagration rather than detonation of the methane air mixture occurred.

FAE operate in a similar way to conventional solid high explosives (HE) in that energy is released by the oxidation of fuel elements, typically carbon and hydrogen, to gaseous products. Whereas for solid HE, oxygen is incorporated within the molecular structure, eg 42% of the weight of TNT is oxygen, FAE uses atmospheric oxygen and so, Kilogram for Kilogram, FAE releases many times more energy than conventional HE. This effect is somewhat diluted by the presence of inert nitrogen in air but overall FAE are two to five times more energetic than TNT.

To continue the comparison, the lower densities of FAE result in lower detonation velocities and pressures within the cloud than within solid HE. However, the pressures are generated throughout the cloud and hence are exerted over larger areas. Moreover because the heats of explosion for FAE are larger, the blast effects outside the cloud are greater for FAE both in terms of overpressure and duration. These characteristics make FAE more effective as blast weapons, ie against personnel, light structures, unarmoured vehicles, ships and parked aircraft, but less effective than solid HE in terms of shattering or brisant properties, ie against armoured vehicles and hardened structures. FAE have also found application in minefield clearance and defoliation of forest and jungle areas.

2. DATA REVIEW

2.1 INTRODUCTION

In this section available data on the subject of FAE is reviewed with the aim of presenting an understanding of the significant factors influencing the design of an effective FAE warhead. Consideration of the application of FAE for military purposes is also discussed.

In order to locate as many relevant references as possible, an on line computer search facility has been used to cover reports, data bases and Chemical Abstracts for material published in the last fifteen years. The computer search output is reproduced at Annex A. Other sources, including those from a manual search of Chemical Abstracts and the use of facilities at the British Science Reference Library, are referenced in the usual way. Information from the literature survey is included in the other sections of this report. Copies of the references obtained up to this point are located in the five associated ring binder volumes. The references in the volumes are those whose reference number is underlined in the Reference section of this report.

2.2 HISTORY

The first military application of fuel air weapons probably occurred as long ago as the eighth century AD when the Byzantines used 'Greek Fire' - an incendiary device to deliver fire to enemy ships. In more recent times flame projectors were used as early as 1914[174] and have since become standard weapons. The development and first use of FAE weapons in which the cloud was intentionally detonated is less well documented in the open literature although FAE devices were used in the Vietnam war. It is clear from the literature however that such devices are under active development in North America and that a number have entered service. Further discussion concerning the application of FAE to military systems is discussed later in Section 2.5.

In addition to the militarily oriented research into FAE, a great deal of related fundamental research on the detonation of fuel air mixtures has been published arising in part from considerations of industrial safety and the transport of flammable gases and liquids. Reviews on the dangers from accidental generation of fuel air clouds[2-4] and from solid suspensions or dusts[5,6] have been published but the emphasis of this report will be on dispersed gases or liquids in air. The formation, detonation and properties of FAE and vapour clouds have been reviewed by several authors[7-26].

2.3 ASPECTS OF DETONATION

It is of fundamental importance both for industrial safety reasons as well as in the designing of effective FAE devices to know whether a particular fuel air cloud can be made to detonate and sustain detonation throughout the cloud. Several factors are important here:

a) the upper and lower limits of the fuel to air ratio that can sustain detonation,

b) the minimum or critical cloud dimension necessary for detonation and

c) the minimum energy of initiation to start detonation.

If the above conditions are not fulfilled then detonation will not be initiated (or once initiated will fail) and the cloud will burn. Experimental determination of predicting fuel air detonability continues and is reported [27-39]. The fulfilment of these criteria are discussed later in Section 5. Most of the early work on the initiation of detonation of FAE concerned the use of HE charges detonated in or near the cloud after dispersal of the fuel[40-58] where the detonation shock wave from the HE caused direct initiation of the cloud. Other methods of initiation have been reported and include chemical[59,60], photochemical[61-63], laser[64,65] and the frictional energy developed by high speed dispersal of liquid fuels[66].

The chemical initiation method appears to be a rather interesting one for FAE weapons. In this method a reactive chemical or chemicals are driven into the cloud using the same bursting charge which disperses the fuel. The chemicals then react together or with the fuel to act as initiators dispersed throughout the cloud, such a FAE weapon is a single event device and removes the need for a second HE initiating device. Successful chemical initiators appear to be bromine trifluoride or chlorine trifluoride as one component systems[59] or silane and perfluorohydrazine as dual component initiators[60]. However, such a method has yet to be demonstrated as a weapon system.

2.4 ASPECTS OF BLAST

Once detonation of the cloud has been initiated the temperature, pressure and velocity of detonation together with the energy release can be calculated using standard computer codes[67] based on the classical Chapman-Jouguet theory (or measured experimentally). The above detonation parameters which are essential in determining the blast effects of a FAE explosion can be predicted surprisingly well by the Chapman-Jouguet theory. This equilibrium theory does not require a knowledge of the structure of the detonation shock wave and it is in this area that significant advances have been made recently[68-84]. Details of the cellular structure of the wave are required to estimate detonability limits, initiation energy, critical tube diameter and reaction zone thickness. The critical diameter has been proposed as an alternative to the critical energy for assessing the relative sensitivity of explosive mixtures to detonation[30]. The critical diameter is the minimum tube diameter from which an emergent planar detonation wave can transmit into free space without failure. Although there is correlation between cell structure and the dynamic detonation parameters above, at present, as mentioned previously, there is no quantitative theoretical relationship[68]. The cellular structure arises from the interaction of combustion waves and shock waves and can be demonstrated or recorded on lightly sooted plates placed in the detonating FAE cloud or by laser-schlieren photography. The characteristic cell size is indicative of the detonability of the FAE cloud: the smaller the cell size the more stable the detonation wave and hence,

1) a lower initiation energy is required,
2) the critical diameter is smaller and
3) the detonability limits are wider(in terms of fuel air ratios).

The critical diameter d_c appears to be related to cell size s by the simple relationship $d_c = 13s$ for all gases studied(68,37) although why this useful relationship holds is as yet unknown.

The great majority of work done on the structure of detonation waves has been carried out in the laboratory under closely controlled conditions using oxygen or oxygen enriched air as the oxidiser and largely under reduced pressure. Whilst many useful data comes from this work it would be difficult to extrapolate these to large unconfined fuel air clouds where for instance the fuel air stoichiometry is varying both with position and time. Although some representative work has recently been published(69,85) much still needs to be done.

A similar position appears to exist on the blast properties of FAE in that the majority of work has been carried out on well defined, well mixed fuel air and fuel oxygen systems(86-90). Numerical models for the prediction of blast properties of such systems have been developed(91-99) and blast measurements of real (non-ideal) FAE systems have been undertaken(100-106). The theoretical prediction of blast properties of practical FAE systems by numerical methods has been proposed(107-108) and recently(97,109,110) good correlation between experiment and theory has been achieved and results from these publications are discussed in more detail in Sections 3 to 8.

2.5 A REVIEW OF LITERATURE ON FAE WEAPON SYSTEMS

The open literature revealed relatively little information on FAE weapon systems and devices partly, of course, for reasons of security. An interesting report concerning the research aspects of FAE weapon development is by Sedgwick and Kratz (125) which covers fuel dissemination, cloud detonation, effects of cloudshape, dwell time, type of fuel, assessment of blast effects, initiation delay time and the feasibility of multiple canister concept for greater ground coverage.

Each of the arms of the US Forces, Army, Air Force, Navy and Marine Corps is pursuing its own programme of research and development of FAE munitions of varying types and size for differing operational roles.

The US Navy exploded its first FAE device in 1960 at China Lake. Following the interest in this and other demonstrations of the period, the US Navy design work on FAE weapons increased under a government Research, Development, Test and Evaluation programme in 1966 at China Lake.

The first US Navy air-dropped operational FAE weapons in the 226 kg (500 lb) class were ready in October 1970 and were deployed in Vietnam[169]. The CBU-55B[127] weapon was used predominantly for defoliation and mine clearance. The CBU-55B is a free-fall cluster-bomb munition. It was deployed on helicopters and the low speed range fixed-wing aircraft. The CBU-55B weighs 226kg and comprises three 45kg BLU-73 canisters 530mm long and 350mm in diameter. A BLU-73 canister contains about 33kg (72lb) of fuel and after release from the aircraft, the individual canisters separate and are retarded by drogue parachutes as they approach the target. The cloud of fuel air mixture produced is about 15m in diameter and 2.4m thick. The cloud is detonated by a delayed action igniter with approximately 125ms delay after bursting. Blast overpressures of up to 20.7 bar (300psi or 210kg/cm^2) have been recorded. The excess pressure in blast wave front at a radius of 15m from the detonation centre is approximately 29kp/cm^2. In Vietnam, this enabled complete defoliation of an area 30m in diameter. The BLU-73 canister had its origin as a ground deployment weapon when a number were placed at the edges of minefields and then detonated by remote control for mine clearance.

Since 1973, there have been attempts to develop a FAE glide bomb for use at speeds of 830 km/h. The tests demonstrated the feasibility of the system for the future. The application of a FAE system for depth charges has also been experimented with tests at depths of up to 700m.

In one instance of testing a FAE weapon design against a hard structure to simulate "a near miss", the Navy placed the weapon on a barge and floated it near a decomissioned destroyer escort, USS McNulty, anchored off San Clemente Island, California, in 27m of water. The distance from the ship when the bomb exploded was kept secret, but the damage was significant. Suffice to say, to avoid the ship sinking in the test area and blocking the channel, it was rapidly towed by tugs into deeper water, where it sank![20]

The CBU-72 resulted from the US Navy's modifications to the CBU-55B to suit it for dropping from high-speed jet aircraft. Specific types from which the CBU-72 was used successfully are the McDonnell Douglas A-4 and the LTV Aerospace A-7. Drogue parachutes to retard the individual canisters were retained. The development of FAE weapons without parachutes for use from high-speed aircraft is a current project area for the US Navy.

Future considerations are for a CBU-72 type system but without a parachute for greater terminal velocity. Other considerations for the future are guidance seekers for this or another high speed version, increase of the warhead size, together with a cloud detonation system incorporated in the missile systems. CBU-72 is delivered up to speeds of 450Kt.

The US Army is interested in adapting one of the CBU-55B bomblets, the BLU-73 warhead, as the basis of a surface-to-surface FAE weapon for clearing minefields. The vehicle used is the Zuni rocket, a number of which are ripple fired from a truck mounted launcher rack. A modified FAU-83 standard mechanical fuze is used to produce varying delays in deployment of the warhead parachutes to achieve an area coverage pattern of FAE detonations. Other FAE systems developed for mine clearance include FAESHED and SLUFAE[126].

FAESHED (Fuel Air Explosives, Helicopter Delivered) is a land mine neutralisation system designed for low intensity conflicts where air superiority is maintained. The technique uses the standard USN CBU-55 FAE munition and standard helicopter stores and bomb racks. The only non-standard item is the fire control box. This is a US Army project and another conducted by the same agency was SLUFAE (Surface Launched Fuel Air Explosive). This consists of a mobile platform carrying an array of 30 launch tubes which can be ripple fired to produce a path through a minefield by the detonation effects of the FAE warheads. It can be fired from a 600m stand off position behind the forward edge of the battle area.

Tests of 155 FAE warheads against over 4,000 mines of US, UK, French, Soviet, Italian and North Vietnamese origin produced 100 per cent kill radii of 8.8m for pressure fuzed mines and 25.9m for pull fuzed trip-wired mines. The latest types of mines with complex, long impulse and double impulse fuzes, including hydraulic long impulse fuzes, seismic/infra-red, electron and magnetic influence fuzes have been detonated successfully or neutralized by FAE blast effects.

By 1967 there was also US Air Force and US Marine Corps activity. Under the Pave Pat programme, the US Air Force carried out tests of a 1134kg (2500lb) weapon. Two versions evolved, BLU-72 and BLU-76 for dropping by A-1 and F-4 aircraft types respectively. However, parachute retarding techniques prevented attainment of the required accuracy.

Following on from this work, the US Air Force have carried out tests of explosive charges of the order of 33.5kg of ethylene oxide. Consideration of 4 sec detonation delay times and delivery speeds of 220 m/s have been made. Further, tests of MAPP (a mixture comprising methyl acetylene, propadiene and propane)have taken place.

Since 1972, the US Air Force in parallel with the US Navy have been developing new generation FAE systems. Both developments (Navy and Air Force) have been under the control of the Weapon Development and Test Center at Eglin Air Force Base.

The US Marine Corps has its own programme for the development of a helicopter deployed FAE system, known as Mass Air Delivery FAE (MADFAE). This system comprises 2 aluminium racks, each containing 12 warheads. The racks are hooked to a helicopter freighthook. A cockpit switch releases the 62kg (136lb) bomblets from the racks. Each dispenser weighs about 226kg (500lb) when empty. Stabilising surfaces are provided to prevent twisting or oscillation of the racks in flight. Single or salvo release of the FAE bombs is possible. Tests have been carried out with CH-46, CH-53 and UH-1 helicopters.

It is interesting to note that as a result of the large area of effectiveness of an FAE weapon, system investigations as to its application as an air defence and space weapon have been made by the USA.

2.6 SUMMARY

In this section a brief history on the applications of FAE has been made together with a short introduction to two important considerations in FAE weapon design: detonation and blast. A review of FAE weapon systems developed in recent years has been made, which indicates the greater degree of activity concerning development of systems in the early 1970's.

3. FUELS

3.1 INTRODUCTION

In accordance with the proposal[1], the requirements for fuel air explosive fuels are that possible fuels for the warhead be available directly from a petroleum refinery and that researched fuels be listed with relevant physical and chemical properties such as vapour pressure, density and energy content. Also calculations of heat of combustion or explosion are to be made. These requirements are covered in this section.

3.2 FUEL AIR EXPLOSIVE REQUIREMENTS

Fuel air explosive fuels should first be easily obtainable as an output from a petroleum refinery. This can mean ordinary, pure hydrocarbons as well as the more familiar but highly complex mixtures such as petrol (gasoline), kerosine, jet fuel (JP4) and diesel fuel.

It should be a liquid with a high boiling point and low vapour pressure at user temperatures which may reach seventy degrees centigrade. Such properties will reduce the need for special warhead containers capable of withstanding the positive pressures that would result from a high vapour pressure fuel standing exposed to direct solar radiation.

A FAE fuel should have a high physical density as well as a high chemical energy density. Although there is a nominal net warhead payload limit of three hundred and sixty kilograms, the warhead size and shape define the true fuel quantity limit by virtue of a volume limit. Accordingly, the highest warhead yields would come from the densest fuels. High chemical energy density would come from those compounds with chemical bond breaks yielding the largest energies.

FAE fuels with the highest Helmholtz free-energy decreases for the explosion process are the most desirable. We have chosen in fact to find energy yields by computing the Helmholtz free-energy function since it, in principle, more nearly gives us the total theoretical amount of energy transferable from an explosive to the blast wave.

FAE fuels should be non-corrosive and chemically stable for long periods of time for the obvious reasons that systems design and container materials problems will be substantially lessened as well as reducing maintenance costs and increasing system reliability. A potential fuel should also be relatively inexpensive since it might be needed in large quantities.

Ideally, a potential FAE fuel should have a demonstrated ability to detonate. Although there is no way to theoretically predict this property, at the very least it should be flammable.

3.3 FUEL SOURCES

The output of a petroleum refinery is the contractually required source for FAE fuels for this program. Accordingly, the potential list of fuels could go into the tens of thousands. However, for the fuel resource to be readily available we must limit the possibilities to the simplest, lowest molecular weight paraffin hydrocarbons. Some of the simpler olefins, cycloparaffins and arometics might also be considered.

Petroleum refineries are more likely to yield very complex mixtures of hydrocarbon compounds the most common of which are petrol (gasoline), kerosine, jet fuel (JP4) and diesel fuel. These are all obtainable by "straight run" fractional distillation of the petroleum crude and though the base composition of the crude can vary considerably, the typical refinery is capable of tailoring the output to any of the standard fuels just listed. The proportion of petroleum products processed from crude petroleum is given in Figure 3.1. A refinery may also, and often does, produce these fuel mixtures by thermal and catalytic cracking as well as thermal and catalytic reforming.

In addition to possible FAE fuels available from petroleum refineries, we wish to also point out that petrochemical plants are a second and possibly important source of potential FAE fuels.

These plants produce fuels other than hydrocarbons which may include such products as ethylene and propylene oxides, ethanol and methanol. The oxides of ethylene and propylene are of particular interest because of their demonstrated effectiveness in military FAE weapons.

3.4 PETROLEUM COMPOUNDS AND MIXTURES

Paraffins have the general formula C_nH_{2n+2}; that is, for every carbon atom there are two hydrogen atoms plus an extra two atoms for each molecule. The simplest member of this series is the familiar methane (marsh gas) CH_4. This and the next member, ethane C_2H_6, are gaseous and are normally not present in gasoline.

In the paraffin, the carbon atoms are linked together as a chain. If the chain is straight, the compound is called "normal", e.g., n-pentane. If the chain is branched, the paraffin is called iso-, e.g., isopentane. In the higher members of the series, there are a large number of branched arrangements. For example, there are 18 different octanes and 75 different decanes.

Olefins have the general formula C_nH_{2n}. They are chain compounds like the paraffins but differ from them in that somewhere in the molecule, two of the carbon atoms are doubly bonded together, eliminating two hydrogen atoms. Their names are the same as the paraffins except that the suffix -ene is substituted for -ane, e.g., butene, pentene. An older form of the names of the simpler members still sometimes given, uses the suffix -ylene, e.g., butylene.

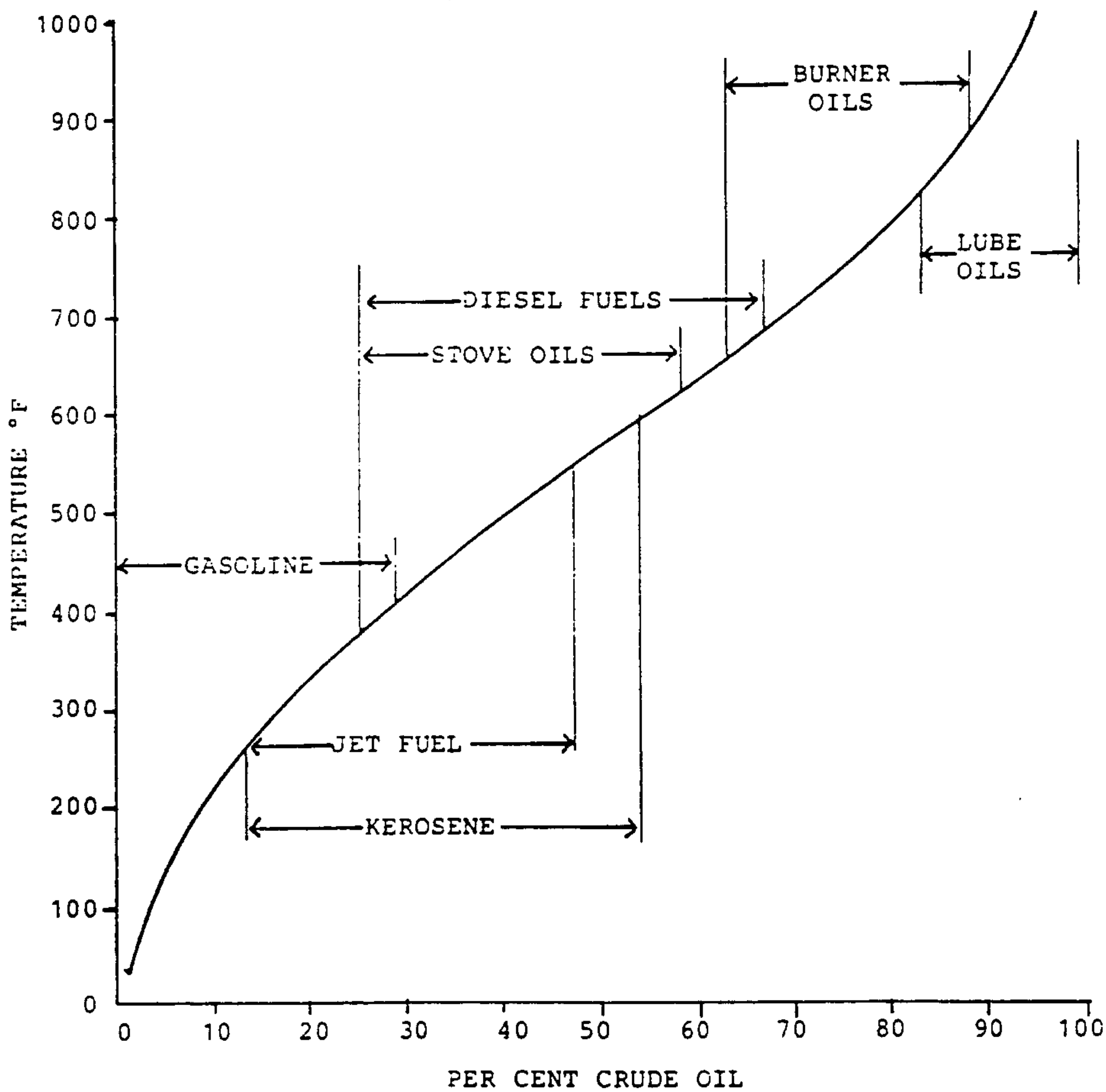

1000
900
800
700
600
500
400
300
200
100
0
TEMPERATURE °F
BURNER
OILS
LUBE
OILS
DIESEL FUELS
STOVE OILS
GASOLINE
JET FUEL
KEROSENE
0
10
20
30
40
50
60
70
80
90
100
PER CENT CRUDE OIL

Figure 3.1

The double bond in the molecule makes possible a greater number of different arrangements of the carbon and hydrogen atoms and there are 66 octenes, for example, as compared with 18 octanes.

Cycloparaffins (naphthenes) have the same general formula C_nH_{2n} as the olefins. They differ from the olefins in that they have no double bonds between carbons but instead contain a ring of five or six carbon atoms to which one or more paraffin chains may be attached, e.g., ethyl cyclohexane, C_8H_{16}.

For the general formula, C_8H_{16}, there are four cyclohexanes and four cyclopentanes, or a total of eight cycloparaffins.

Aromatics have the general formula C_nH_{2n-6}. Their molecules contain a characteristic structure known as the benzene ring. This is a ring of six carbon atoms to each of which is attached only one hydrogen. One or more of these hydrogens may be replaced by paraffin chains. The simpler members are benzene C_6H_6, toluene C_7H_8, xylene C_8H_{10}. There are four different xylenes and eight C_9 aromatics.

Gasoline is a mixture consisting almost exclusively of hydrocarbons. There are probably several hundred different hydrocarbons in various proportions in any one gasoline. Most however, are light paraffins.

Kerosine (approximately 325°F to 575°F boiling range) and wide-cut (approximately 125°F to 575°F boiling range) types of fuels are generally straight-run stocks taken directly from selected crudes by fractional distillation. Kerosine is usually made by a single cut. Wide-cut fuels such as JP4 can be made the same way, or they may be a blend of a kerosine boiling fraction plus a lighter stock such as heavy straight-run gasoline or another material in this boiling range. The blend can be pressurized to specification requirements with relatively high vapour pressure materials such as butanes or pentanes as necessary.

Jet fuels made from straight-run stocks consist primarily of paraffinic, naphthenic and aromatic types of hydrocarbons.

Prior to World War II, the aromatic naphthas were produced by the fractional distillation of coal tar and coal-tar residues. These included benzene, toluene and xylene which may be potential FAE fuels. With technical developments and the adoption of new processes in petroleum refining, a high proportion of these aromatics, plus other types of aromatics not previously available, are now produced by the petroleum industry. In general, however, the aromatics from either source are essentially the same in all respects, with the possible exception of a few specific organic chemical materials originally based on coal tar. The conventional qualities of products from the two sources, such as boiling range, solvency and so on, are the same. In fact, the new processes now used in petroleum refining are producing intermediate- and high-boiling-point types of naphthas that are not available from coal-tar sources.

3.5 FUEL ENERGY CALCULATIONS

The fuel energy available in a FAE explosion may be arrived at in many ways including computing the heat of explosion, computing the energy of explosion, computing or looking up in tables the heat of combustion, or by experiment. We shall illustrate the computational methods using the relatively simple case for a conventional explosive, TNT. The techniques are similar for FAE except for the limitation that the explosion products are not known in detail.

3.5.1 Heat of Explosion

The thermal energy released by the explosive decomposition of a given explosive is in principle easily measured experimentally. The technique is like that for the measurement of the calorific value of a fuel and is as follows:

1) a small but known amount of explosive is placed in a bomb calorimeter along with an arrangement to initiate its explosion;

2) a few drops of water are added to ensure complete condensation of any water formed in the products, the bomb calorimeter is purged of air and pressurized with helium (or nitrogen) to avoid combustion effect;
3) the material is exploded and
4) the heat transferred to the calorimeter is measured by noting the temperature rise.

The measured heat value, per unit quantity of explosive, is termed the heat of explosion.

A thermodynamic analysis of the process occurring in the calorimeter during the measurement of the heat of explosion is quite conventional. The products formed are combined within the bomb and are not permitted to perform expansion work; rather they are merely cooled from explosion temperature to calorimeter temperature. The resulting heat flow constitutes the so-called heat of explosion. Also, the thermal capacity of the calorimeter is comparatively great and its net temperature change is small, hence the terminal temperatures for the overall process are substantially identical. That is, the process is isothermal. Thus the heat of explosion corresponds to an isothermal internal energy decrease for the system as a result of the spontaneous explosion, or

$$-\Delta E = \text{heat of explosion} = -(E_2 - E_1) \qquad (3.5\text{-}1)$$

where ΔE represents the internal energy of the system, in this case that of some specified quantity of explosive (E_1) or of its products (E_2).

The fact that the products of explosion are not fixed in nature introduces uncertainty into the exact meaning to be attached to the so-called "heat of explosion" of Eqn. 3.5-1. An experimental measurement with more precise meaning is to be preferred, at least for some purposes. One such definite measurement is that of a heat of combustion. Here the reaction in the calorimeter is caused to be a relatively simple combustion in the presence of excess oxygen supply and the products formed are the result of a complete combustion to carbon dioxide, water and molecular nitrogen. The results obtained then correspond to the basic thermodynamic characteristics of the explosive, and as such do have definite and precise meaning. Using the conventional methods of physical chemistry, these data may be organized and presented in various ways; one convenient way is in the form of values for the internal energy of formation. From the measured values for the internal energy of formation, a heat of explosion may readily be computed for any given products composition, including that which by chance occurs in some particular calorimeter. The computation is illustrated in Example 1, in Section 3.5.4 to follow, where nominal products of explosions are assumed.

The computation of a heat of explosion from these formation data proceeds by first specifying the products to be considered and then finding the internal energy values for these products and for the explosive. The difference in these corresponds to the heat of explosion, as shown in Eqn. 3.5-1. The computation customarily ignores minor items such as the effect of pressure levels, mixing or solution effects and those of non-ideal gas behaviour. Required are data on internal energy of formation. These are given in Table 3.1. For a material whose internal energy of formation has not been measured, there are available approximation methods based on group increments and in some instances these may suffice to provide a reasonable estimate.Table 3.2 lists increments for some of the groups of interest in the chemistry of explosives. It should be noted that the group increment approxmations in Table 3.2 utilizes the modern sign convention, where decreases in magnitude of a thermodynamic property are considered to be algebraically negative.

3.5.2 Energy of Explosion

The amount of energy transferable from an explosive to a blast wave is a key item in the study of explosions. This flow of energy can be evaluated in terms of gas volume v and pressure P as work of expansion, $\int_{P_1}^{P_2} Pdv$, performed by the pent-up gases produced in the explosion, but precise evaluation of this

THERMODYNAMIC PROPERTIES OF PRODUCTS OF EXPLOSION (25°C)

		ΔE_f^o	ΔH_f^o	ΔA_f^o	ΔF_f^o	S^o
O	(g)	58.863	59.159	54.698	54.994	38.4689
O_2	(g)	0.00	0.00	0.00	0.00	49.003
H	(g)	51.793	52.089	48.279	48.575	27.3927
H_2	(g)	0.00	0.00	0.00	0.00	31.211
O	(g)	10.06	10.06	8.93	8.93	43.888
H_2O	(g)	-57.5016	-57.7979	-56.3394	-54.6357	45.106
	(l)	-67.421	-68.317	-56.793	-56.690	16.716
N	(g)	85.272	85.565	81.175	81.471	36.6147
N_2	(g)	0.00	0.00	0.00	0.00	45.767
NO	(g)	21.600	21.600	20.719	20.719	50.339
NO_2	(g)	8.387	8.091	12.686	12.390	57.47
NH_3	(g)	-10.45	-11.04	-3.383	-3.976	46.01
C	(g)	171.105	171.698	160.252	160.845	37.7611
(diamond)		0.4352	0.4352	0.6850	0.6850	0.5829
(graphite)		0.00	0.00	0.00	0.00	1.3609
CO	(g)	-26.7220	-26.4157	-33.1042	-32.8079	47.301
CO_2	(g)	-94.0518	-94.0518	-94.2598	-94.2598	51.061
BO	(g)	-5.6	-5.3	-11.9	-11.9	12.91
B_2O_3	(c)	-301.1	-302.00	-282.1	-283.0	12.91
(glass)		-296.7	-297.6	-279.5	-280.4	18.8
HBO_2	(c)	-186.0	-186.9	-169.6	-170.5	11.00
BN	(c)	-32.4	-32.1	-27.5	-27.2	8.00
Al_2O_3	(c)	-389.20	-399.09	-375.88	-376.77	12.186
Na_2O	(c)	-99.1	-99.4	-89.7	-90.0	17.4
Na_2CO_3	(c)	-269.4	-27.3	-249.5	-250.4	32.5
Cl	(g)	28.716	28.012	24.896	25.192	39.4567
Cl_2	(g)	0.00	0.00	0.00	0.00	53.286
HCl	(g)	-22.063	-22.063	-22.769	-22.769	44.617
CCl_4	(l)	-24.9	-25.5	-14.7	-15.3	73.95
$COCl_2$	(g)	-53.0	-53.3	-50.0	-50.3	69.13
F	(g)	18.0	18.3	13.9	14.2	37.917
F_2	(g)	0.00	0.00	0.00	0.00	48.6
ClF	(g)	-13.3	-13.3	-13.6	-13.6	52.05
ClF_3	(g)	-36.4	-37.0	-26.6	-27.2	66.61
HF	(g)	-64.2	-64.2	-64.7	-64.7	41.47
CF_4	(g)	-161.9	-162.5	-151.2	-151.8	62.7
AlF_3	(c)	-311.0	-311.0	-294.0	-294.0	23.0
HF_3	(g)	-265.1	-265.4	-261.0	-261.3	60.70
KCl	(c)	-103.869	-104.175	-98.296	-97.592	19.56
KF	(c)	-134.16	-134.16	-127.12	-127.42	15.91
KHF_2	(c)	-220.28	-210.90	-204.03	-203.73	24.92
K_2O	(c)	-86.1	-86.4	--	--	--
K_2CO_3	(c)	-274.23	-273.93	--	--	--
LiF	(c)	-246.0	-146.3	-139.3	-139.6	8.57
LiCl	(g)	-53.0	-53.0	-58.0	-58.0	51.01
	(c)	-97.4	-97.7	--	--	--

(g) Gaseous; (l) Liquid; (c) Crystalline

ΔE_f^o - Standard internal energy of formation, kilocal per gram mole.

ΔH_f^o - Standard enthalpy of formation, kilocal per gram mole.

ΔA_f^o - Standard Helmholtz free energy of formation, kilocal per gram mole.

ΔF_f^o - Standard Gibbs free energy of formation, kilocal per gram mole.

S^o - The absolute (or third-law) entropy, cal per gram mole per °K.

See "Selected Values of Chemical Thermodynamic Properties." Circular 500, Nat. Bur. of Stds., 1952, for additional items

TABLE 3.1

GROUP INCREMENT APPROXIMATIONS

Group Increment	A	B
substitute $-CH_3$ for -H, aliphatic	4	5
aromatic	2	6
remove 2 -H to form double bond	20	0
remove 4 -H to form triple bond	70	-7
substitute $-C_6H_5$ for -H	45	17
substitute -OH for H to form an alcohol	-35	0
to form a phenol	-40	1
insertion of -O- linkage to form an ether	-20	0
insertion of -CO-O- to form an ester	-70	5
substitution of -CHO for -H to form an aldehyde	-20	6
substitution of -O for 2 H to form a ketone	-30	1
substitution of -COOH for H to form an acid	-25	6
subsitute $-NH_2$ for H to form an amine	0	0
substitute -CN for $-CH_3$ to form nitrile	35	13
substitute -CI for H	0	6
substitute -S for -O- to form a thioether	35	2
substitute $-NO_2$ for -H, aliphetic	-10	7
aromatic, first	-20	8
aromatic, other than first	0	7
substitute $-NO_2$ for -H of amine, to form nitramine	15	5
substitute $-ONO_2$ for H, to form a nitrate ester	-20	6
for -OH, to form nitrate ester	25	5
add HNO_3 to form nitrate salt of an amine	-70	7
substitute $-HN-NO_2$ for -h to form nitramine	15	5

A = Change in Internal Energy of Formation, kcal/gm mole
B = Change in Entropy

Representative Parent Compounds (25 °C and 1 Atmosphere)

Compound		C	D
Normal paraffin hydrocarbons, C_nH_{2n+2}	(liquid)	-9-5.6(n)	25+7.7(n)
	(solid)	-6-6.6(n)	18+5.6(n)
Benzene, C_6H_6	(liquid)	13.5	43.6
	(solid, hypothetical)	11.2	35

C = Internal Energy of Formation
D = Entropy

See G.V. Janz, Estimation of Thermodynamic Properties of Organic Compounds, New York, Academic Press, 1958, for a survey of approximation methods.

line integral can be quite troublesome. It requires a knowledge of the initial pressure generated in the explosion and also the pressure-volume relations for a complex mixture of non-ideal gases whose temperature is changing and whose composition is difficult to establish. Further complexities enter if the process is not adiabatic and appreciable heat losses occur. Such losses, however, are ordinarily minor, except perhaps in underwater explosions where substantial cooling effects may exist.

An alternative to the troublesome evaluation of the line integral above is to make an over-all thermodynamic analysis directly in terms of terminal values of pertinent thermodynamic properties. Such an analysis indicates

(1) The maximum energy release that may be obtained in a given explosion is representable as an isothermal decrease in the Helmholtz free-energy function (also referred to as work content.)

(2) A change in value for the Helmholtz free-energy function A is a simple difference in point functions A_2 for the explosion products and A_1 for the original materials.

(3) The difference in Helmholtz free-energy represents a limiting or theoretical value and any actual explosive energy release may be less than this.

Discrepancies between the theoretical limiting and the actual explosive energy release can result from the following conditions:

(1) The explosion may be accompanied by some degradation of energy (that is, it may not be reversible);

(2) Heat losses may occur so that the gases expand at lesser volume; and

(3) The temperature of the products after their expansion to ambient pressure is not necessarily identical with ambient temperature. Experience has indicated, however, that none of these items is a major factor. Hence to a fair approximation the Helmholtz free-energy decrease for the explosion process is an adequate measure of the

energy actually available for explosive yield, as well as serving as an index of the maximum amount theoretically available.

The Helmholtz free-energy is by definition the algebraic difference between the internal energy and the temperature-entropy product. That is

$$A = E - TS$$

where A is the Helmholtz free-energy function, E the internal energy, T the absolute temperature and S the entropy. Thus

$$\text{Energy of explosion} = \int_{P_1}^{P_2} P dv = -\Delta A = -\Delta E + T\Delta S \qquad (3.5\text{-}2)$$

where $-\Delta E$ is the internal energy decrease measured as the heat of explosion and ΔS the entropy growth for the (isothermal) process. The entropy of a store of energy is an index of its unavailability; the greater its entropy the less this energy is available for performing work. All spontaneous processes represent some loss in availability and hence are accompanied by entropy growth. Equation 3.5-2 assumes that during the explosion process the necessary increase in entropy (or loss in availability) is accompanied by a maximum flow of energy into explosion blast.

Let us compare the relative significances of the calorimetrically measured "heat of explosion" of Eqn. 3.5-1 and of the "energy of explosion" of Eqn. 3.5-2. It can be seen that the former is solely a thermal item and that it ignores the energy obtainable from expansion of highly compressed gases formed in the explosion. That is, in a calorimeter any energy of expansion is dissipated irreversibly as in a throttling process and quite as in the classic Joule experiment. But in an ordinary explosion the expansion of these gases may contribute appreciably to the energy transferred to the blast wave. Thus it frequently happens that the aggregate of the kinetic and internal energies in the hydrodynamic field of the blast wave exceeds the energy release which can be measured in the calorimeter. There is a correlation with the items of Eqn. 3.5-2, where the magnitude of the free-energy decrease exceeds that of the internal energy decrease.

The change in the Helmholtz free-energy in an explosion can in principle be computed from data such as the free energy of formation of the explosive and that of the products of explosion. Unfortunately, there are almost no such data available for explosives, most of the investigative work in this field having been of a more practical nature such as shooting bullets at samples of the material. In the absence of the needed basic information, approximation methods may be used to provide rough estimates for theoretical explosive performance. These methods are somewhat indirect. They first assume a products composition and then they estimate a corresponding decrease in internal energy and a corresponding growth of entropy in the explosion process. These two separate items are then combined, as in Eqn. 3.5-2.

3.5.3 Entropy of Explosion

The entropy of explosion represents the entropy growth in the transformation from explosive to products. As for the products, when the nature of these is known their entropy is rather simply a weighted assumption of individual values for each species. For a product that conforms to the specification of the ideal gas, the individual entropy per mole, S, is given as

$$S = S^o - R\ln p \qquad (3.5\text{-}3)$$

where S^o is the standard molar entropy at unit pressure and the specified temperature. Here R is the molar gas constant (1.987 cal/gm-mole, ^oK) and p represents the partial pressure of the gas (in atmospheres). The term $-R\ln p$ is sometimes identified as an "entropy of mixing". For a mixture of ideal gases at a total pressure of P atmospheres, a given component with mole fraction y exhibits a partial pressure p = yP and a molar entropy

$$S = S^o - 2.303\ R\log_{10}y - 2.303\ R\log_{10}P \qquad (3.5\text{-}4)$$

where the term to the right drops out if the total pressure is one atmosphere. Table 3.3 provides numerical values for the item $-R\ln y = -2.303\ R\log_{10}y$.

Equations 3.5-3 and 3.5-4 apply only to gaseous components, and assume the ideal gas laws. For components which are solids or liquids, the entropy is relatively unaffected by pressure, hence the individual entropy per mole at any pressure may be taken as being the standard entropy.

For the computation of the theoretical explosive yield it is also necessary to know the entropy of the explosive itself. But the basic properties of many explosives are not readily available and it may become necessary to rely on approximation methods. However, the entropy for most solid materials is not a large item so that for solids an approximation based on the group increments of Table 3.3 may be reasonably acceptable. Alternatively an approximation may be based on the observation that, very roughly, for many solid organic compounds,

$$S^o = 15 + 5n \qquad (3.5\text{-}5)$$

where n is the number of all atoms present except hydrogen and oxygen. (The constant 15 provides for the hydrogen and oxygen components.) The entropy of liquid materials is in general greater than that for solids by an amount related to the entropy of fusion; for some purposes it has been assumed that the entropy of a liquid is about 40 percent greater than that for the corresponding solid.

Computations for the theoretical energy of explosion and thus also for theoretical explosive yield, are subsequently illustrated in Examples 3 to 5 in Section 3.5.4. Using the methods outlined, the heat of explosion for TNT is computed as being about 649 calories per gram, in reasonable agreement with measured values. The entropy of explosion is computed to be

ENTROPY AND FREE ENERGY OF MIXING

Entropy of Mixing. Cal per gram mole - °K, - R ln y, where y represents the mole fraction of an ideal gas, and R the molar gas constant, 1.98719 defined cal per gram mole - °K.

Free Energy of Mixing. Kilocal per gram mole at 25°C, RT ln y, where y is the mole fraction of an ideal gas, R the molar gas constant 0.0019871 kilocalories per gram mole - °K, and T the reference temperature of 298.16°K (25°C or 77°F).

y	-R ln y	-RT ln y	y	-R ln y	-RT ln y
.00	---	0.000	.30	2.391	.723
.01	9.145	2.727	.32	2.263	.675
.02	7.769	2.316	.34	2.142	.639
.03	6.963	2.076	.36	2.029	.605
.04	6.392	1.906	.38	1.921	.573
.05	5.949	1.774	.40	1.820	.543
.06	5.589	1.666	.42	1.723	.514
.07	5.282	1.575	.44	1.631	.486
.08	5.016	1.496	.46	1.543	.460
.09	4.782	1.426	.48	1.458	.435
.10	4.573	1.363	.50	1.377	.411
.11	4.383	1.307	.52	1.299	.387
.12	4.211	1.256	.54	1.224	.365
.13	4.052	1.208	.56	1.152	.343
.14	3.904	1.164	.58	1.082	.323
.15	3.767	1.123	.60	1.016	.303
.16	3.639	1.085	.62	0.949	.283
.17	3.519	1.049	.64	0.886	.264
.18	3.405	1.015	.66	0.824	.246
.19	3.298	0.983	.68	0.766	.228
.20	3.196	.953	.70	0.709	.211
.21	3.099	.924	.72	0.652	.194
.22	3.007	.897	.74	0.598	.178
.23	2.919	.870	.76	0.545	.162
.24	2.834	.845	.78	0.493	.147
.25	2.753	.821	.80	0.443	.132
.26	2.675	.796	.85	0.323	.096
.27	2.600	.775	.90	0.207	.062
.28	2.528	.854	.95	0.102	.030
.29	2.458	.733	1.00	0.000	.000

about 385 entropy units per gram mole of TNT. The corresponding $T \Delta S$ term of Eqn 3.5-2 becomes about (298 x 385/227) = 506 calories per gram. The sum $-\Delta E + T \Delta A = +649 + 506 = 1155$ calories per gram, giving a theoretical (maximum) that is in good agreement with the value 1120 deduced from blast-wave measurements. Not only is the discrepancy between computed and experimental values quite small, it is also in the expected direction.

In computation of a theoretical explosive yield and of a heat of explosion it is convenient to assume the formation of liquid water (equivalent to a "higher heating value" in combustion). The latent heat of vaporization of any water product is thereby included in the ΔE term, as occurs in experimental calorimetric measurements made at room temperature. However, the $T\Delta S$ term of Eqn. 3.5-2, is correspondingly reduced, so that the effect of this assumption on the values computed for the overall energy of explosion is quite negligible, for there is a nearly complete compensation between the internal energy and the entropy terms of Eqn. 3.5-2.

The explosive yield calculations indicated above are somewhat indirect, for a composite item is involved. It is quite feasible, however, to organize the required data into a form which permits a more direct computation. This calculation requires values for the Helmholtz free-energy function for the explosives and for the products at their partial pressures (rather than at unit pressure). For ideal gases it may be shown that

$$A = A^{o} + RT\ln p \qquad (3.5\text{-}6)$$

where A^{o} is the standard Helmholtz free energy value,
p the partial pressure of a component gas,
R the gas constant and
T the absolute temperature.

Expressed in terms of its mole fraction y and for a total pressure of P atmospheres, this becomes, for ideal gases

$$A = A^{o} + 2.303\ RT\log_{10}y + 2.303\ RT\ \log_{10}P$$

These equations make it possible to find the effect of mixing on the Helmholtz free-energy for each component of an ideal gas mixture (Table 3.3). The energy of explosion can then be computed directly, provided the properties of the explosive and the nature of its products of explosion are known.

Equation 3.5-6, when combined with Eqn. 3.5-2, also permits a calculation of the limiting amount of energy available from the explosive expansion of a store of compressed gas. Assuming n moles of ideal gases and no chemical or nuclear transformation, then for the idealized limiting situation of isothermal expansion

$$\text{Energy of Explosion} = \int_{P_1}^{P_2} P dv \simeq T\Delta S = nRT \ln(P_1/P_2) \qquad (3.5\text{-}7)$$

where T is the absolute temperature,

P_1 the original (absolute) pressure of the compressed gas and

P_2 the final or atmospheric pressure.

This equation affords a simple means for estimating an approximate TNT equivalent of an explosion due, for example, to the sudden failure of gas tank (see Ex. 5). Equation 3.5-7 involving the molar or universal value of the gas constant R indicates that this explosive energy release depends on the number of moles of gas rather than on the mass. For the many situations in which the various assumptions of isothermal expansion, ideal gases, etc., are not appropriate, evaluation of the integral of Equations 3.5-2 or 3.5-7 may be required. An example is the calculation of the amount of energy released in the explosion of a steam boiler, or by the smokeless powder in a shotgun barrel.

Equation 3.5-7 may be regarded as representing a sort of extreme or limiting situation in which there is no chemical energy release, hence the E term of Eqn. 3.5-2 is not pertinent. Another limiting situation is an explosion in which a negligible amount of gases are produced; that is, where the $T \Delta S$ term of Eqn. 3.5-2 drops out. This situation is approached in lightning flashes and in nuclear explosions.

3.5.4 Illustrative Examples

Example 1. Compute the theoretical value for the heat of explosion of TNT from its internal energy of formation, assuming a nominal distribution of oxygen in the products of explosion.

The formula for TNT in condensed form is $C_7H_5O_6N_3$, its formula mass is 227 and its internal energy of formation is given as -13.0 kilocal/gm-mole. It can be seen that the nominal oxygen distribution in the products of its explosion calls for six moles of carbon monoxide, one atom of solid carbon, etc. A material balance for this assumed decomposition may be written in the form of a chemical equation using chemical formulae in their usually accepted (quantitative) significance. The standard internal energy of formation for each component is written below the formula for each material.

material balance	$C_7H_5O_6N_3$	C +	$6\ CO$ +	$2.5\ H_2$ +	$1.5\ N_2$
E^o	-13.0	0	-26.722	0	0

The internal energy change for the assumed transformation is the difference in values for the total amount of products components and for the explosive.

$$\Delta E = (\Delta E^o)_2 - (\Delta E^o)_1 = (6 \times -26.722) - (-13.0)$$
$$= -147.3 \text{ kilocal per gm-mole.}$$

This internal energy decrease per mole corresponds to a heat of explosion of (147,300/227) = 649 cal per gm, which conforms reasonably well with directly measured values.

Example 2. Compute an entropy of explosion for TNT, assuming a nominal products of explosion at a total pressure of one atmosphere. The entropy of pure TNT has been measured as about 65 cal per gm-mole -°K at 25°C.

The material balance for the assumed decomposition is written in the form of a chemical equation and the entropy for each component ascertained.

material balance	$C_7H_5O_6N_3$	C +	$6\,CO$ +	$2.5\,H_2$ +	$1.5\,N_2$
S^o	65	1.361	47.301	31.211	45.767
-4lnp	--	-----	1.016	2.753	3.767
S	65	1.361	48.317	33.964	49.534

With regard to the individual entropy items, these for the solid TNT and the solid carbon are taken as the standard values. For gaseous components the standard entropy S^o is corrected by adding on the entropy of mixing, as called for by Eqn. 3.5-4, and obtained perhaps from Table 3.3.

The entropy of explosion is the difference in values for the total amount of material for concern.

$$\Delta S = S_2 - S_1 = (1.361 + 6 \times 48.317 + 2.5 \times 33.964 + 1.5 \times 49.534) - 65$$
$$= 385.5 \text{ entropy units}$$

Example 3. Compute a theoretical value for the energy of explosion of TNT using the values obtained above for the heat of explosion and the entropy of explosion.

The internal energy decrease was computed in Ex. 1 as 147.3 kilocal, or 147,300 cal, per gm-mole. Combining with the entropy of explosion as computed in Ex. 2, assuming a standard temperature of 25°C (298.16°K) and utilizing Eqn. 3.5-2.

$$\Delta A = \Delta E - T\Delta S = -147{,}300 - (298 \times 385.5) = -262{,}180 \text{ cal/moles}$$

This decrease in value for the Helmholtz free-energy function corresponds to an explosive energy release of (262,180)/(227), or 1155 cals per gm. This theoretical maximum is in good agreement with the observed value of about 1120 cals per gm, the discrepancy being at least partially attributable to irreversibilities in the detonation process.

<u>Example 4.</u> Estimate the relative explosive strength of trinitrobenzaldehyde, using approximations based on group increments.

Searching for a "parent" compound of as similar a structure as possible and for which data are available, a logical choice seems to be TNT. The formula for TNT, $C_6H_2(NO_2)_3$, can be transmuted into that for trinitrobenzaldehyde, $C_6H_2(NO_2)_3CHO$, by the substitution of an aledhyde -CHO group for a methyl $-CH_3$ group.

The internal energy of formation of TNT is given as -13.0 kilocal per gm mole at 25°C and its entropy is known to be about 65 entropy units at that temperature. To transmute TNT into trinitrobenzaledehyde then requires

(1) the substitution of -H for $-CH_3$ in aromatic compounds and
(2) a substitution of -CHO for -H. By Table 3.3, the internal energy of formation for trinitrobenzaledehyde is estimated as -13.0-(+2)+(-20) = 35 kilocal per gm mole. Likewise its entropy is estimated as 65-6+6-65 entropy units.

Computation of the theoretical energy of explosion from these proceeds as in Ex. 1,2 and 3 above.

<u>Example 5.</u> Compute the explosive energy available and its TNT equivalent from the compressed air in a tank of 2.00 cu ft capacity if at 3000 psia. Assume ideal gas behaviour and a temperature of 25°C (298°K).

To use Eqn. 3.5-7 and obtain values in calories, it is convenient to express R as 1.987 cal per gm-mole-°K. For this purpose the mass of air must be converted into terms of gram moles.

number of lb-moles of air = $\frac{2 \times (3000/14.7) \times (273/298)}{359} \simeq 1.04$

where 359 represents the number of cu ft per lb-mole of ideal gas at standard pressure of 1 atmosphere and temperature of 0°C. This corresponds to 1.04 x 454, or 473 gm-moles of air. By Eqn. 3.5-7,

$-\Delta A = 564 \times 1.987 \times 298 \ln(3000/14.7) \simeq 1{,}490{,}000$ cal total.

This is the equivalent of 1.49×10^{-3} defined tons of TNT, or about 3.3lb.

SYMBOLS

A	= Helmholtz free energy, E - TS
°C	= Centigrade (Celsius) temperature
E	= Internal energy per mole
°K	= Kelvin (absolute Centigrade) temperature, C + 273.16
m	= Mass of an object
n	= A number
P	= Absolute pressure
p	= Partial pressure of a gas component
R	= Gas law content (1.98719 defined cal per gm mole -°K)
S	= Entropy per mole
T	= Absolute temperature
v	= Volume
W	= Explosive energy release, expressed as pounds of TNT
y	= Mole fraction of a gas component
Δ	= (Delta) a small incremental unit

superscript

o	= Indicates standard value at unit pressure

subscript

f	= Indicates formation value
1	= Indicates initial value
2	= Indicates final value
ln	= Natural logarithm to base e
log	= Logarithm to base 10

3.6 FUEL EXPERIMENTAL DATa

Although the calculation of FAE explosion energy is straight forward in principle it is very difficult to do with significant accuracy because the reaction products and proportions are not well defined. For example the explosion (combustion) of cyclohexane may be ideally described by the equation:

$$2\ C_6H_{14} + 19\ O_2 \longrightarrow 12\ CO_2 + 14\ H_2O \qquad (3.6\text{-}1)$$

Calculation of the heat and energy of explosion depends on the reaction products 12 CO_2 and 14 H_2O. On the other hand, an incomplete reaction with numerous intermediate products, some possibly involving oxides of nitrogen as well, may look like this:

$$?C_oH_{14} + ?O_2 + ?N_2 \longrightarrow ?CO_2 + ?CO + ?H_2O + ?NO + ?NO_2$$

It is remarkable in fact that Equation 3.6-1 can give an experimentally verified answer within a factor of ten. Indeed some theoretical literature on the subject incorporates a constant to correct for these realities which ranges from 0.01 to 0.3. This is saying that the ideal case varies from 1% to 30% of the experimentally observed case.

The case is similar for fuel detonability. There exists no theoretical way to predict whether a flammable fuel will detonate or not. The terms burn, deflagrate, explode, detonate, etc. are distinguished by the velocity of the reaction propagating through the fuel. The slowest is burning which can be of the order of a few metres per second while the fastest detonation can be thousands of metres per second. There is some indication in the literature that the more energetic the detonation charge, the more likely a given fuel will detonate. A preliminary search of the FAE literature reveals that propane, heptane, ethylene oxide, propylene oxide, petrol (gasoline), kerosine, diesel fuel, acetylene and aluminium powder have been experimentally shown to detonate.

3.7 FUEL CONSIDERATIONS

With a view to obtaining a feel for the merits of various fuels for the warhead of the ballistic missile, the energy of the fuels has been calculated. The fuels considered and the necessary figures needed to obtain the total specified warhead energy are presented in Table 3.4.

The first column in Table 3.4 contains a list of fuels considered.

The column headed 'A' identifies with a 'Y', those FAE fuels that have been demonstrated to detonate.

Column B gives the density in grams per cubic centimetre of the fuel as a liquid at 20°C. Note that propane, butane and ethylene oxide are normally gases at standard temperature and pressure.

Column C gives the calculated energy of explosion as described in Section 3.5.2.

Column D gives the heat of combustion of various fuels. The heat of combustion represents the energy released by the complete burning of the fuel. The inconsistencies in the relative values of the heat of combustion and energy of explosion for the individual fuels is due to the difficulties in measuring the energies in the combustion process on the one hand and adequately defining the explosion processes on the other. Nevertheless, except in the case of decane, the contradictions are small compared to the magnitude of related unknowns in the FAE weapons picture such as targeting accuracy. Where values are missing in columns C and D they are either unknown or not calculable.

Column E lists the total fuel mass in kilograms that the warhead could contain. To calculate the quantity of FAE fuel the missile can carry, it is necessary to know the warhead shape and volume. The details of the warhead configuration

FUEL LIST

Fuel	A	B	C	D	E	F	G
1. Propane	Y	.51	11,300	11,000	375	5760	4.[illegible]
2. Butane		.58	13,400	11,000	406	7770	5.[illegible]
3. Pentane		.63	11,100	11,600	441	7310	5.[illegible]
4. Hexane		.66	11,400	10,700	462	7520	5.[illegible]
5. Heptane	Y	.68	11,200	11,500	476	7620	5.[illegible]
6. Decane		.75	13,400	10,600	525	10000	7.[illegible]
7. Benzene		.88	9,450	10,100	616	8890	6.[illegible]
8. Toluene		.87	9,650	10,100	609	8790	6.[illegible]
9. Xylene		.86	10,200	10,300	602	8860	6.[illegible]
10. Methanol		.79	5,560	5,300	553	4390	3.[illegible]
11. Ethanol		.79	6,800	7,100	553	5610	3.[illegible]
12. Ethylene Oxide	Y	.87	6,920	6,800	609	6020	4.[illegible]
13. Propylene Oxide	Y	.83	7,900	7,600	581	6560	4.[illegible]
14. Hydrazine		.98	2,800	-----	686	2744	1.[illegible]
15. Gasoline	Y	.68	---	10,200	476	6940	4.[illegible]
16. Jet Fuel (JP4)		.78	---	10,200	546	7960	5.[illegible]
17. Kerosine	Y	.80	---	10,200	560	8160	5.[illegible]
18. Diesel Fuel	Y	.84	---	10,200	588	8570	6.[illegible]
19. Acetylene	Y	.60	---	12,000	---	----	---

A = Is the fuel known to detonate? (Y=Yes, Blank = Not Known to)

B = Density (g/cm^3)

C = Calculated Energy of Explosion (cal/g)

D = Heat of Combustion (cal/g)

E = Fuel Mass in Specified Warhead (Kg)

F = Figure of Merit: Maximum Energy per Unit Volume (cal/cm^3)

G = Total Specified Warhead Energy ($cal \times 10^9$)

TABLE 3.4

will be treated in the final report, but for the purpose of these calculations we have assumed a two metre high right circular cone atop a one metre high right circular cylinder with an inside diameter of 0.79 metres. This gives a net maximum volume of 0.8 cubic metres after subtracting for burster and detonater charges and fuzing.

Column F gives the volume figure of merit for each fuel. This is the maximum explosion energy in calories per cubic centimetre of fuel.

Column G contains the total explosion energy potentially available in the warhead described earlier if it were completely filled with the designated fuel. The units are in 10^9 calories.

From this analysis and assuming that warhead energy is the appropriate measure of effectiveness decane, benzyne, toluene, xylene, kerosine and diesel fuel are the more preferable fuels.

3.8 SUMMARY

In this section various fuels for a FAE warhead have been identified and calculations made to ascertain their energy yield. The list of fuels in Table 3.4 (described in Section 3.7 above), although not exhaustive, does contain the more feasible for consideration. Of those considered however, not all are promising. For instance, hydrazine is very difficult to handle and has a relatively low energy yield. Methanol and ethanol are easy to handle but they too have a relatively low energy yield as well as no demonstrated ability to detonate. Ethylene and propylene oxides are well known FAE fuels but they are not products of a petroleum refinery.

An important factor in the selection of a preferable fuel is, of course, the energy it yields, however at this point in the study other considerations are necessary before any ranking criteria can be drawn up. For the present however, kerosine appears as attractive a fuel as any, since it has been demonstrated to detonate, it is easily obtainable from a petroleum refinery, it is easy to handle and it ranks high in explosive energy content among the fuels on the list.

4. AEROSOL CLOUD FORMATION

4.1 AEROSOL DEFINITION AND CHARACTERISTICS

An aerosol is any solid or liquid particulant suspension in air. A great range of other terms have been used to describe particulate systems in air as well: dust, smoke, fume, haze and mist are all words in common use with somewhat different but related meanings. Dust usually refers to solid particles produced by disintegration processes, while smoke and fume particles are generally smaller and formed from the gas phase. Mists are composed of liquid droplets.

Aerosols are formed either by the conversion of gases to particulate matter or by the disintegration of liquids or solids. They may also result from the resuspension of powdered material or the break-up of agglomerates. Formation from the gas phase tends to produce much finer particles than disintegration processes (except when condensation takes place directly on existing particles). Particles formed directly from the gas are usually smaller than $1\mu m$ in diameter.

The lifetime of an undisturbed aerosol cloud is quite long compared to the times of interest to us even though suspension of small particles in gases at high concentrations are unstable; the particles collide and coagulate as a result of the Brownian motion. The time to reduce the particle concentration to one-tenth its original value by coagulation can be calculated from theory. Table 4.1 shows values of this characteristic time as a function of concentration, N_o (the number of drops per cm^3), for the coagulation of a monodisperse aerosol with particle diameter $d_p = 0.1\mu m$. From the table it is quite evident that the lower the aerosol concentration, the longer it takes to reduce that concentration. This time changes relatively little with particle size for monodisperse systems.

TIME TO REDUCE THE CONCENTRATION N_0, OF A MONODISPERSE AEROSOL TO ONE-TENTH THE ORIGINAL VALUE, $N_0(d_p=0.1\mu m,\ T=20^{\circ}C)$

$N_0 cm^{-3}$	$t_{1/10}$ (approximate)
10^{10}	1.2 sec
10^9	12 sec
10^8	2 min
10^7	20 min
10^6	3.5 hr
10^5	35 hr

Table 4.1

It is sometimes thought that fuel vapours are necessary for the effective detonation of a FAE cloud, but fortunately, this is not so, for the evaporation rate of even higher pressure fluids is too slow for FAE weapons. A vapour is a dispersion of the fuel in the atmosphere at the molecular level, whereas aerosol droplets contain innumerable molecules condensed together. Figures 4.1 and 4.2 illustrate typical evaporation times showing that evaporation is not a linear process with time.

Droplet size is determined largely by wind velocity and fuel viscosity as illustrated by the typical curves of Figures 4.3 and 4.4.

4.2 CLOUD DISPERSION

FAE clouds are usually dispersed by placing a small explosive burster charge along the axis of the fuel cylinder. The expanding gases from the explosion then push the fuel outward breaking its volume successively into smaller and smaller drops until each individual drop has fuel stripped from it to form microdrops that are detonable. The stripping process develops as waves are developed in the drop.

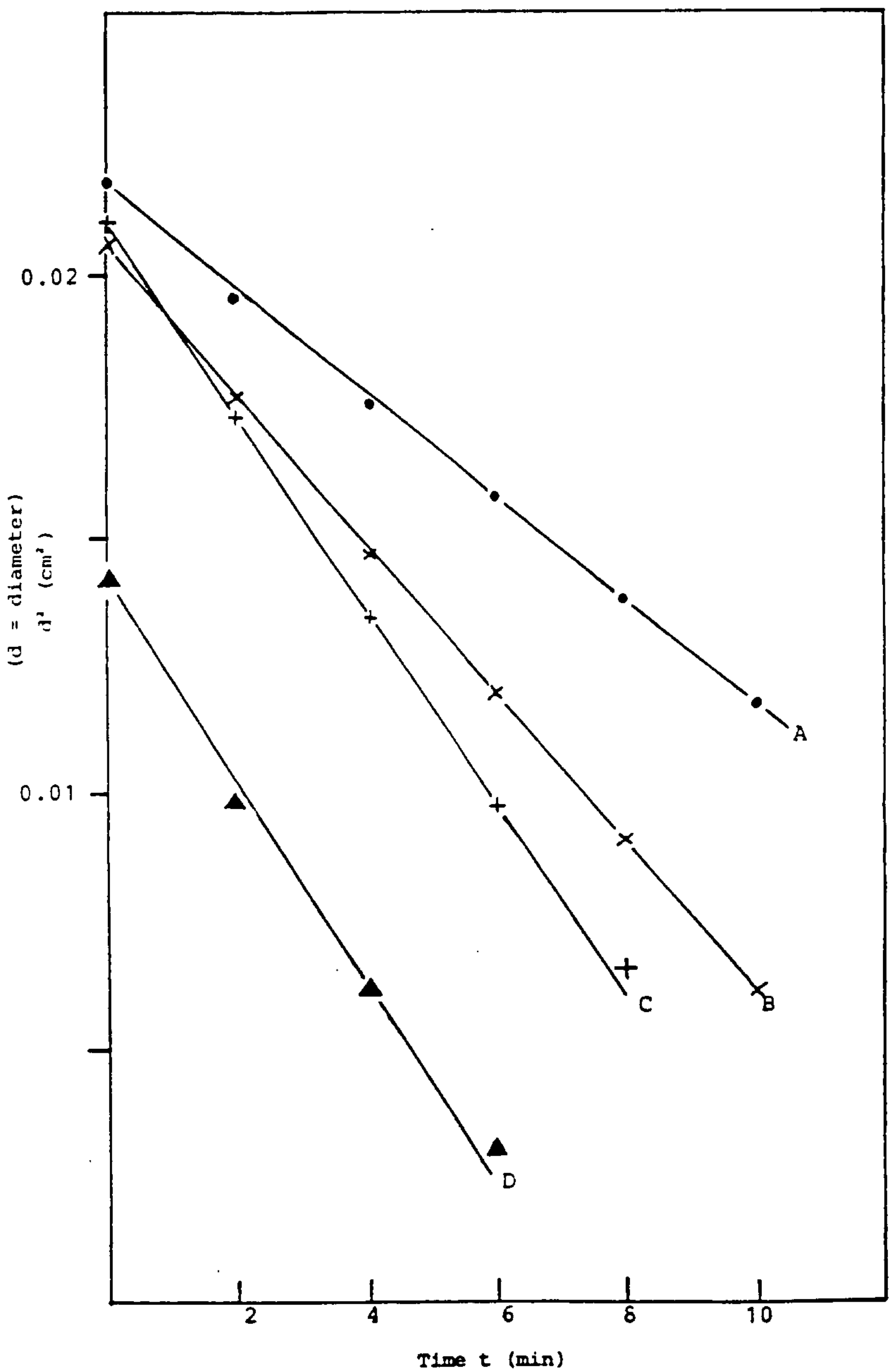


Figure [illegible] Evaporation of drops of furfural in air

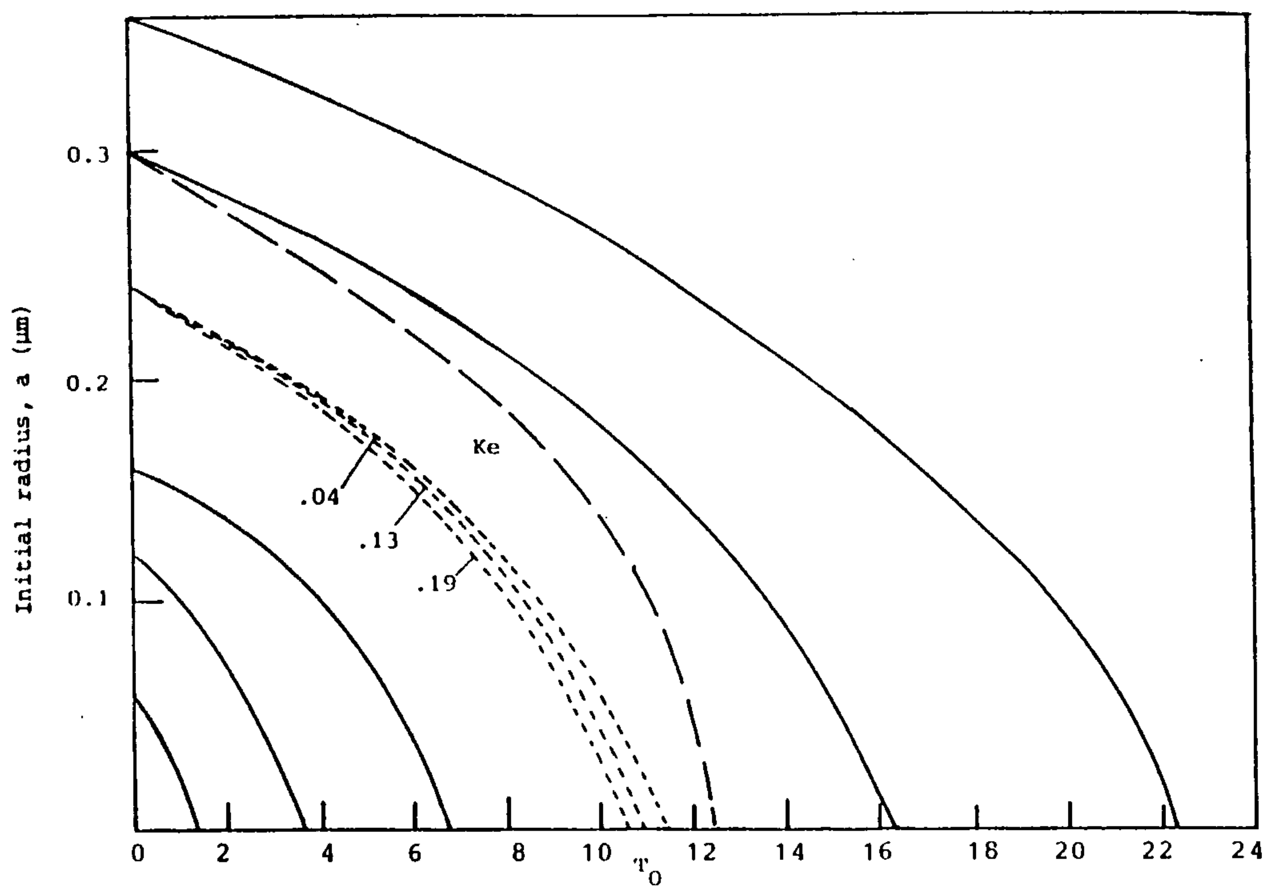
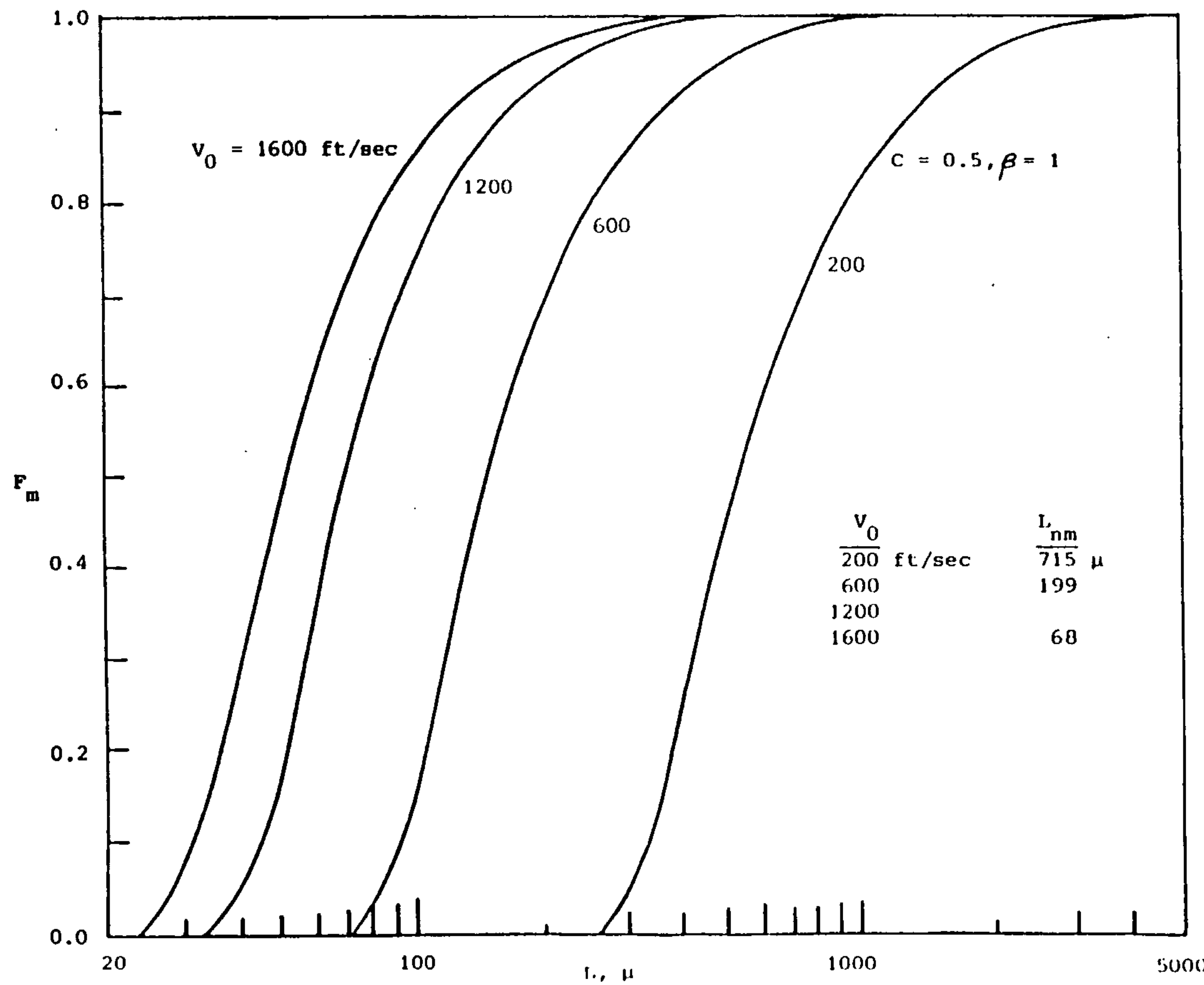


Figure 4.2 Evaporation of fine droplets into vapourfree air at 20 °C and 1 atm., with allowance for Kelvin effect and free molecular flow at surface (Ke=0.1). Initial radii 0.06, 0.12, 0.16, 0.30, 0.36 μm, with allowance for Kelvin effect and free molecular flow at surface (Ke=0.04, 0.13, 0.19). Inital radius 0.24 μm, with allowance for Kelvin effect alone. Diffusion control. Initial radius 0.30 μm.


1.0
0.8
0.6
0.4
0.2
0.0
F_m
V_0 = 1600 ft/sec
1200
600
200
C = 0.5, β = 1
V_0 | L_{nm}
200 ft/sec | 715 μ
600 | 199
1200
1600 | 68
20
100
1000
5000
L, μ

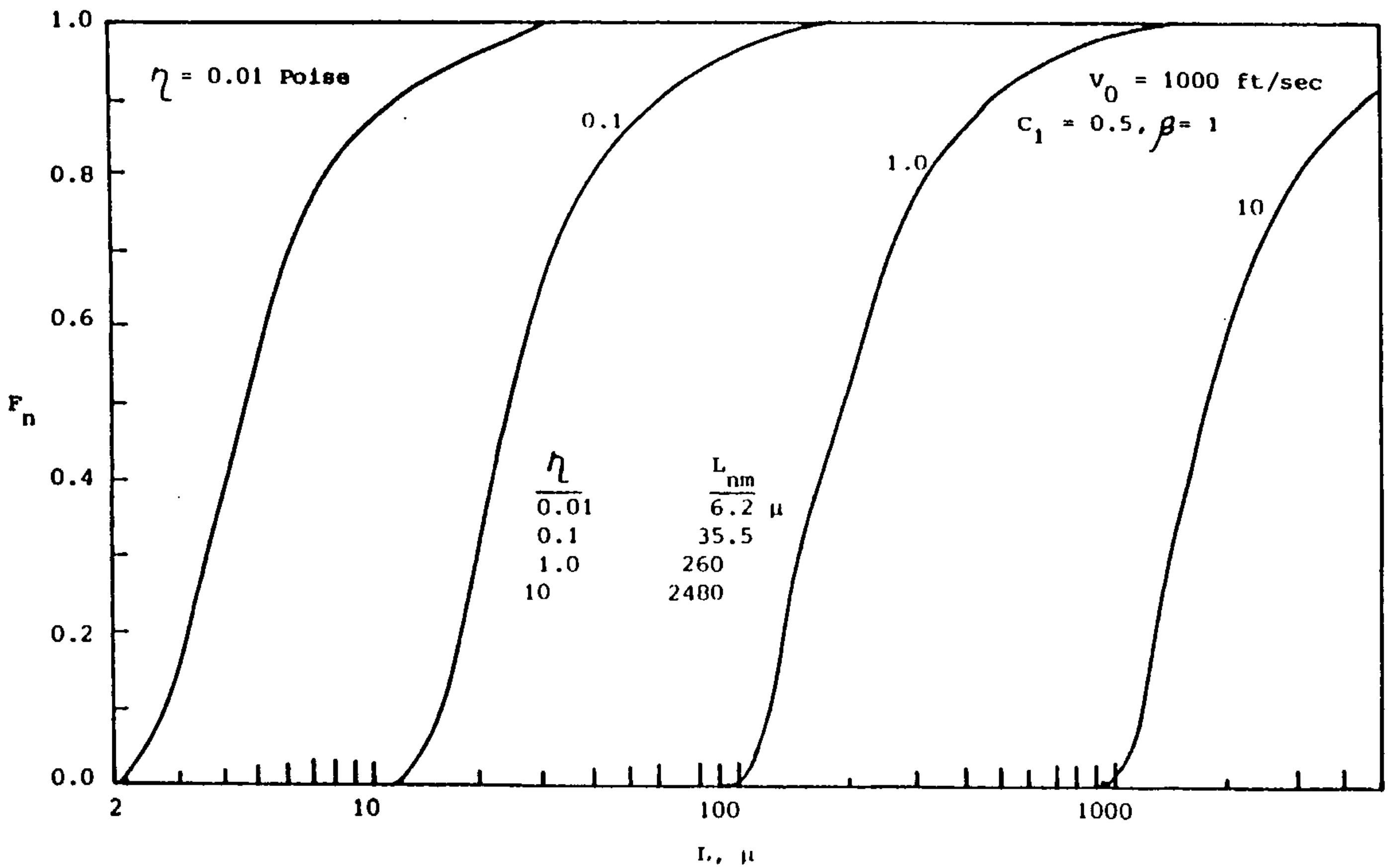


Figure 4.4 Effect of Fluid Viscosity on the Number Fraction Distribution

According to theory the mean droplet size produced by the primary stripping of a liquid is proportional to the two-thirds power of the fluid viscosity (or effective viscosity) for capillary waves and the first power for acceleration waves. The power lies between these values for the combined model, depending on conditions. The viscosity dependence of the mass mean droplet diameter produced by primary breakup also depends on the stripping conditions (relative velocity and fluid viscosity) as well as on the size of the liquid undergoing stripping, but its value can be much smaller than the preceding values (2/3 to 1 power). On the other hand, under conditions that secondary breakup can occur the viscosity dependence of the final (observed) mass mean droplet size appears to be related to the viscosity dependence of the particular waves that control the final breakup.

As discussed previously, the primary stripping breakup of a liquid produces a spectrum of particles (drops) whose sizes range from the minimum size, which is determined by wind velocity and fluid viscosity, to the maximum size which is proportional to the linear dimensions of the liquid. A portion of these drops then continue to undergo secondary (and higher order) breakup during their drag deceleration to a stable size.

The drop breakup time depends on the initial diameter D_o exposed to an aerodynamic flow which causes the drop to undergo surface stripping. The time rate of decrease of the mass of the drop is $(-dm/dt)=(-\rho_1 \pi D^2/2)(dD/dt)$ and this mass loss rate is equal to the wind stripping rate of the drop, i.e., $\dot{M}f_1(\pi D^2/2)$, where the drop is assumed to undergo stripping on some effective fraction, f_1, of its frontal surface area. Since the drop undergoes a certain degree of deformation and spreading during its stripping, the parameter f_1 accounts for the average area that undergoes stripping during the lifetime of the drop in terms of the equivalent sphere frontal area of the drop. Integrating the preceding equation gives the effective equivalent sphere diameter of the drop at any time during its stripping, i.e.,

$$D - D_o = -f_1\dot{M}L/\rho_1$$

The time to reduce the diameter to essentially zero size gives the stripping breakup time of the drop, i.e.,

$$t_b = \frac{\rho_1 D_o}{f_1 M}$$

4.2.1 Primary Breakup

The mass stripping rate, $\dot{M}$ (gm/cm^2 sec), of liquid particles from the cylindrical liquid slug contained on the missile travelling with velocity, V is given by

$$\dot{M} = \frac{K_o \rho_l}{L_2 - L_1} \left[\frac{f}{a}(B-A) - \frac{fE}{2a^{3/2}} - g \ln \frac{L_2}{L_1} \right] \quad (4.2\text{-}1)$$

where, $$E = \ln \left[\frac{B + a^{1/2} L_2 + (1/2\, a^{1/2})}{A + a^{1/2} L_1 + (1/2\, a^{1/2})} \right]$$

$$A = (L_1 + a L_1^2)^{1/2}$$

$$B = (L_2 + a L_2^2)^{1/2}$$

$$f = (\pi / 2\rho_l \sigma)^{1/2} \beta \rho V^2$$

$$g = 8\pi^2 C_2 \eta_e^{1/2} / \rho_l$$

$$a = C_1 C_d \rho V^2 / 4\pi^2 \sigma$$

ρ_1, ρ and η_e are the density, surface tension and effective viscosity of the liquid, p is air density, K_2, C_1 and C_2 are model constants and C_d is the drag coefficient. In the solution of Eqn. 4.2-1, L_1 is considered to be the minimum wavelength, L_{min}, induced on the liquid surface by the aerodynamic wind, which is given by the smallest positive root of the equation:-

$$L^3 - a(g/f)^2 L - (g/f)^2 = 0$$

L_2 is the maximum wavelength, L_{max}, which is given by

$$L_{max} = eD_o$$

where D_o is the diameter of the liquid and e is a model constant.

In the solution of Eqn. 4.2-1 for a Newtonian fluid, η_e is constant. However, for a non-Newtonian and/or elastic liquid the effective viscosity varies with the shear rate, $\dot{S}$, which is related to the surface stripping rate by

$$\dot{S} = 2/\tau \qquad (4.2\text{-}2)$$

where

$$\frac{1}{\tau} = \frac{f}{(L + aL^2)^{1/2}} - \frac{g}{L^2} \qquad (4.2\text{-}3)$$

The solution of Eqn. 4.2-1 should then be carried out on an incremental wavelength basis, using the simultaneous solution of Eqn. 4.2-2 and the experimental relation between η_e and $\dot{S}$ for the fluid in order to obtain the η_e for use in a particular wavelength increment of Eqn. 4.2-1. The effective viscosity is related to the experimental apparent viscosity, η_a , and recoverable shear, s (both of which may depend on the shear rate) by

$$\eta_e = \eta_a(1+s)$$

The consistency of Eqns. 4.2-2 and 4.2-3 with the experimental $\eta_e = f(\dot{S})$ relationship must also be observed in all other calculations involving non-Newtonian and/or elastic fluids.

The droplet stripping rate, $\dot{N}$ (droplets/cm^2 sec), from the liquid cylinder is given by

$$\dot{N} = K_1 (L_2 - L_1)^{-1} \left\{ \frac{4f}{3} \left[\left(\frac{a}{L_2}\right)^3 - \left(\frac{A}{L_1}\right)^3 \right] - 2f \left[\frac{B}{L_2^2} - \frac{A}{L_1^2} \right] - \frac{g}{3} \left[\left(\frac{1}{L_1}\right)^3 - \left(\frac{1}{L_2}\right)^3 \right] \right\}$$

where K_1 is a constant.

The primary droplet size distribution produced by the liquid stripping, based on the cumulative number of droplets, is given for a Newtonian fluid by

$$F_n = \int_{L_{min}}^{L} \dot{N}\, dL \Big/ \int_{L_{min}}^{L_{max}} \dot{N}\, dL \qquad (4.2\text{-}4)$$

F_n is the fractional number of droplets having a size between d_{min} (the minimum droplet diameter) and any droplet diameter d, where d is related to wavelength, L by

$$d = FL \qquad (4.2\text{-}5)$$

and F is a constant. For a non-Newtonian fluid the equations must be solved on an incremental wavelength basis. Then

$$F_n = \frac{\sum_{L_{min}}^{L} \int_{L_1}^{L_2} \dot{N}\, dL}{\sum_{L_{min}}^{L_{max}} \int_{L_1}^{L_2} \dot{N}\, dL} \qquad (4.2\text{-}6)$$

The primary droplet size distribution produced by the liquid stripping, based on the cumulative droplet mass, is given by equations similar to Eqns. 4.2-4 and 4.2-5 with F_m replacing F_n and M replacing N, where F_m is the fractional mass of droplets having a size between d_{min} and any d and M is given by Eqn. 4.2-1.

The number mean wavelength, L_{nm}, over the entire wavelength distribution, is given by

$$L_{nm} = \frac{2f\,(A/L_1 - B/L_2) - (g/2)(L_1^{-2} - L_2^{-2})}{(L_2 - L_1)\dot{N}/K_1} \qquad (4.2\text{-}7)$$

The mass mean wavelength, L_{mm}, is given by

$$L_{mm} = \frac{\rho_1 f\,(BD_m - AC_m + 3E/8a^{5/2}) - \rho_1 g\,(L_2 - L_1)}{(L_2 - L_1)\dot{M}/K_2} \qquad (4.2\text{-}8)$$

$$C_m = L_1/2a - 3/4\,a^2$$

$$D_m = L_2/2a - 3/4\,a^2$$

The number of mean and mass droplet diameters are obtained by combining Eqns. 4.2-7 and 4.2-8 with Eqn. 4.2-5.

4.2.2 Secondary Breakup

The secondary (and higher order) breakup calculations begin by partitioning the cumulative mass fraction droplet size distribution (F_m vs d) produced by the primary breakup of the liquid into a number of contiguous zones (about 10) in which all the droplets in each zone are considered as having the same (averaged) properties, size and velocity. The droplet mass in the various zones is then considered to undergo stripping on an incremental time basis, which shifts the mass in the various zones towards zones of smaller droplet diameter according to the stripping rate equation

$$\Delta m \;\propto\; \ddot{M} f_1 \pi D^2 \Delta t$$

where $\dot{M}$ is given by Eqn. 4.2-1, D is droplet diameter and f_1 is a constant.

Conservation of mass is maintained over the zones and the number of droplets in each zone is computed from the mass. The change in droplet velocity over a prescribed time increment (while stripping is occurring) is due to drag droplet formation and momentum balance and is given by

$$\Delta V = \Delta V_{drag} + \Delta V_{drop} + \Delta V_{mom.}$$

$$\Delta V_{drag} = \frac{-3 C_d \rho V^2}{4 \rho_1 D}$$

$$\Delta V_{drop} = -C_3 L \dot{S}$$

$$\Delta V_{mom.} = n M_{in} (V_{in} - V) / M$$

where C_3 is a constant and

M_{in} is the mass brought into the zone with velocity, V_{in},

V is the original zone velocity and

M is the total zone mass.

4.3 BURSTER CHARGE

The burster charge used for FAE dispersal has been composed of several explosives. The type is not critical; with experiments using TNT, RDX and composition C-4 among others. The quantity required varies somewhat with fuel density and amount but generally amounts to three quarters to one percent of the fuel mass.

4.4 CLOUD SHAPE AND STRUCTURE

The overall FAE cloud shape can be tailored somewhat to the target requirements. The typical shapes will most likely be hemispherical or toroidal. The toroidal case will give a higher peak overpressure over a larger area than the hemispherical case for a fixed quantity of fuel. It is not clear whether this is due to the obvious geometric advantage or to reinforcement of the blast wave from a horizontally larger source cloud.

The FAE cloud will also have structure related to the nature of the fuel container. For example, one might find substantial "spikes" superimposed on a hemispherical cloud that are artifacts of the rupture seams in the fuel canister. However, it appears from the literature that this may not be a serious problem.

The ability to compute the cloud radius for a given quantity of fuel is important. Several models exist for this purpose, the most straight forward using simple geometric considerations. Assuming a typical weight for weight fuel air ratio of 6% we have

$$0.06 = \frac{m_F}{m_A} = \frac{m_F}{\rho_A V_A}$$

where m_F is the mass of fuel,

m_A is the mass of air,

ρ_A is the density of air, and

V_A is the appropriate volume of air contained in the desired FAE cloud shape, i.e., $2/3 \pi R^3$ for a hemisphere, $\pi R^2 h$ for a cylindrical cloud, etc.

Accordingly, for the hemispherical case, we have, the radius R,

$$R = 2 \left(\frac{m_f}{\rho_A} \right)^{1/3}$$

From this equation 400Kg of propane would give a cloud radius of 14m.

More elaborate models take into account droplet size, fuel, viscosity, etc. For example the final length, L_c (containing most of the liquid mass), of the particle cloud that is produced by the stripping of the liquid cylinder is given by

$$L_c = L_b + L_t = L_b/Q = 1.64(L_o/Q)(\rho_l/\rho)^{1/2}$$

$$L_b/L_c = Q = 1.268 - 8(10^{-4})\ V_o + 2(10^{-7})V^2 \qquad (4.4\text{-}1)$$

where V_o is the missile speed (in ft/sec),

ρ and ρ_l are the air and fuel densities respectively,

L_o is the length of the cylindrical liquid slug undergoing breakup.

L_b is the dispersal particle cloud at the end of the primary break up and

L_t is the travel distance before the particle starts to break up.

The final width, W_c, of the particle cloud (containing a significant fraction of the total liquid mass) is given by

$$W_c = 0.63\ d^{0.958}V^{0.375}Q^{0.25}n_e^{-0.042}$$

where W_c is in ft,

d_o is the liquid slug diameter (in inches),

V_o is missile speed (in ft/sec),

Q is given by Eqn. 4.4-1, and

n_e is the effective viscosity of the fluid (in poise).

4.5 SUMMARY

Formation of the aerosol cloud depends in detail on a number of physical properties of the FAE fuel. Low viscosity is desirable because it eases the creation of small, explodable drops. Low fuel density is an advantage because it permits these small droplets to be created faster thereby avoiding droplet coalescence which will rob the FAE cloud of usable fuel. It is fortunate that all of the fuels listed in Table 3.4 have relatively low viscosity and density so that special dispersion techniques are not necessary. The literature has numerous examples of successful FAE cloud dispersion using one percent of fuel weight in a TNT burster charge axially mounted in the fuel cylinder. The desired diameter of the fuel cloud for a given quantity of fuel will depend in part on the combustion chemistry of the fuel. Nevertheless, with four hundred kilograms of a typical hydrocarbon a hemispherical cloud on the order of 28 metres diameter will be near the optimum size. Further calculation for specific fuels are underway and will be presented in the final report.

5. AEROSOL CLOUD DETONATION

5.1 BACKGROUND

It is now well known that the classical theory of a detonation which regards a detonation wave as a strictly one-dimensional structure consisting of a shock wave followed by a reaction zone is an adequate description of the detonation phenomena. Numerous detailed investigations of the structure of detonations over the past 50 years have shown that the propagation of a detonation is a complex three-dimensional phenomena involving the interactions of finite amplitude transverse waves with the leading shock front, the reaction zone and the boundaries of the system. Although the three-dimensional transverse wave structure of detonation is observed for unconfined detonations, the most detailed investigations of this structure have been done in confined rectangular or round detonation tubes. In these cases, in particular for conditions marginal to the propagation of the detonation wave (i.e., close to the detonability limits), the influence of the tube walls cannot be neglected.

The tube walls have two different effects; namely, an energy and momentum loss associated with the boundary layers and a stabilizing effect on the transverse wave structure. For small diameter tubes the observed decrease in velocity with decreasing tube diameter can be understood in terms of the influence of the boundary layers. On the other hand, it is also observed that an apparently self-sustained detonation in a confined tube fails once it emerges into an area expansion or an unconfined region. For a given mixture there appears to be a minimal critical tube diameter required in order for the detonation to continue to propagate under confined conditions. It has been suggested that this critical tube diameter is related to the characteristic transverse wave of the detonation. In other words, a minimum number of transver[illegible] waves is required for a self-sustained detonatio[illegible] unconfined situation, thus indicating that the pr[illegible] three-dimensional structure observed in tubes ne[illegible] detonability limits is stabilized by the confinement [illegible]

A possible relation between the spinning detonations observed in tubes and the detonability limits has been discussed in the literature where it has been suggested that the condition for stable propagation of a detonation wave in a tube is for the reaction time to be short enough to maintain the spin mode of the lowest frequency in the tube. Thus if the onset of the single-head spin structure corresponds to a unique fuel composition, the limit could be defined on this basis. Associated with this limit there would then be a characteristic chemical length scale which can be related to the tube diameter and geometry using the acoustic theory of spin detonation. The success of the acoustic theory in predicting the frequency or pitch of the transverse or spinning vibrations observed behind the detonation by the boundary conditions and do not depend on the details of the coupling between the gasdynamics and the chemical kinetics which give rise to the transverse instability in the first place. The only condition being that the reaction time or chemical time be short enough to maintain the spinning mode.

The mechanism by which the transverse waves are excited and maintained is not completely understood. However, it has been shown that acoustic and non-linear perturbations can be amplified through the coupling with chemical energy release. The amplitudes and wavelengths of the perturbations required to trigger the various instabilities are not known. However, it appears that detonations are unstable to perturbations over a fairly wide range of wavelengths.

The acoustic kinetic interactions depend on the order and the enthalpy of the reaction, the activation energy and most important of all the ratio of the characteristic acoustic time to the chemical time. This is further supported by the stability limits of detonations for various degrees of overdrive assuming a first order Arrhenius rate expression. Although the range of wavelengths over which the detonation is unstable depends on the activation energy and the degree of overdrive, one finds that the detonations are stable only at short wavelengths (i.e. short compared to the length of the reaction zone), and also at long wavelengths for sufficiently

It appears that transverse waves with wavelengths over a fairly wide range can be excited. Thus the transverse wave structure of a detonation will depend on the preferred transverse mode. This preferred mode will be determined not only by the gasdynamic- chemical kinetic coupling, but also by the boundary conditions (for example, the geometry and diameter of the detonation tube). As long as the characteristic transverse dimensions associated with the boundary conditions are much larger than the characteristic wavelength associated with the chemical kinetics and gasdynamics, the boundary conditions will play a minor role in determining the transverse wave structure. However, for tube diameters of the order of the characteristic transverse wavelength or smaller, the boundary conditions will begin to play a more dominant role, so that for the same mixture the detonation phenomena observed in a small diameter tube could be completely different to that which would be observed in an unconfined situation or in situations with different boundary conditions. Not only could the structure of the detonation wave be different, but composition limits of detonability could also vary with boundary conditions. In fact, it may be possible to trigger "detonation" phenomena in a tube outside of the limits of detonability for an unconfined situation. The phenomena of "galloping" detonations may be an example of such a phenomena.

If this is the case and if the onset of the "galloping" mode is sufficiently precise, then the onset of the "galloping" mode could also provide a criteria for determining the detonability limits. The "galloping" mode is a longitudinal mode with periodic destruction and reformation of the detonation where the reformation process is identical to the transition form deflagration to detonation. "Galloping" detonations can therefore be considered to consist of periodic transitions, in which case the tube walls and confinement are known to play an important role. However, the role of the transverse waves, which are observed in near limit mixtures in maintaining the detonation wave is not understood.

Most fuel-oxygen gas mixtures can be detonated. If a detonating mixture is diluted with an inert gas such as nitrogen, there then exists a particular oxygen to nitrogen ratio below which the mixture can no longer be detonated. If this oxygen to nitrogen ratio is less than about 0.25 (composition of air), the fuel will also detonate when mixed with air. However, no exact quantitative theory currently exists whereby one can predict, a priori, whether a given fuel-air mixture can detonate, and if so, what the detonability limits are. Neither can one predict whether a flame can accelerate to a detonation in this mixture, or whether the detonation can be initiated directly via a powerful explosive charge.

5.2 EXPLOSIVE DETONATION

Generally speaking, there are two modes of initiation: a slow mode where the detonation is formed via an accelerating flame and a fast mode where the detonation is formed "instantaneously" when a sufficiently powerful igniter is used. The slow mode is usually referred to as the transition from deflagration to detonation. Turbulence and interactions between pressure waves and flame are the principle flame-acceleration mechanisms that generate the critical states for the onset of detonation. In general, the ignition source plays the dominant role in the fast mode of initiation. The blast wave generated by the igniter energy produces the necessary critical states for the onset of detonation. The fast mode is referred to as direct initiation, since the detonation is formed directly without a predetonation deflagration regime. It is also referred to as blast initiation in some recent literature to emphasize the role that the blast wave plays in the initiation processes. It would be appropriate to call the slow mode of transition from deflagration to detonation self-initiation because the detonation is caused solely by the energy release from the combustion of the mixture itself in the predetonation regime. The parameters that characterize these two modes of initiation are the transition distance for self-initiation and the igniter energy for direct initiation. The basic initiation mechanisms associated with these two modes are understood quite well on a qualitative basis.

Direct or blast initiation is the fast mode in which the detonation is formed in the immediate vicinity of the powerful igniter. The igniter must be capable of not only generating a strong shock wave, but of maintaining the shock above a certain minimum strength for some required duration. For a given igniter, the energy of the igniter characterizes the phenomenon. Below a certain threshold value of the ignition energy, it is found that the blast wave generated by the igniter will progressively decouple from the reaction front. The blast wave decays to a sound wave, and the subsequent propagation of the reaction front is identical to an ordinary flame. This has been referred to as the subcritical regime.

If the ignition energy exceeds the critical threshold value, the blast and reaction front are always coupled in the form of a multiheaded detonation wave that starts at the source and expands at about the Chapman-Jouguet detonation velocity. This is referred to as the supercritical regime.

When the ignition energy is at the critical threshold value, the phenomenon is more interesting. For very early times, the blast and reaction front are coupled. As the blast expands, the decoupling occurs and the reaction front recedes from the shock. However, the decoupling process soon terminates when the chemical energy released by combustion begins to contribute significantly to the blast motion. The blast no longer decays, and the shock wave and the reaction front then propagate as a coupled complex at a constant velocity. This is called the quasi-steady period of the blast motion, and during this period, the blast strength corresponds approximately to the autoignition limit of the mixture. The duration of the quasi-steady regime corresponds approximately to the induction time at the auto-ignition temperature. The termination of the quasi-steady regime is marked by the sudden appearance of a localized explosion. However, it is evident that reestablishment is identical to the onset of detonation in self-initiation. In direct initiation, the conditions for the onset of detonation are formed by the reacting blast-wave generated by the igniter. For self-initiation or the transition mode discussed previously, these same critical conditions are derived from the acceleration of the flame itself.

5.3 CHEMICAL DETONATION

The possibility exists of chemical detonation of a FAE warhead. Laboratory studies have shown that light FAE hydrocarbon fuels as well as diesel oil can be detonated by the injection of elemental fluorine, chlorine trifluoride or bromine trifluoride into the aerosol cloud.

This method of detonation has some very attractive advantages over the conventional explosive "second event" detonation for it eliminates altogether the need for a separate detonation device and synchronization. The detonation is achieved by the "first event" burster charge which causes the detonating chemical to be injected into the fuel simultaneously with fuel dispersion. It is important to note however that this has not yet been achieved with a deployable FAE weapon.

5.4 DETONATION ENERGY AND DELAY

The explosive detonation energy threshold for FAE clouds is a function of the fuel type and the ratio of fuel to air. A typical comparison of the critical energies for acetylene-oxygen mixtures obtained using various igniters is shown in Figure 5.1. The critical energy versus composition curve demonstrates a characteristic U-shape. The minimum limiting value of the spark energies is generally an order of magnitude less than the exploding wire energies on the basis of the total $CV^2/2$ energy stored in the capacitor.

The dependence of the critical energy on composition is qualitatively the same for most detonating gases. The sharply increasing trends in the initiation energy for fuel-lean and fuel-rich compositions, namely, the vertical arms of the U-shaped curve, are in fact used to determine experimentally the composition limits of detonability of explosive gas mixtures. Accordingly, any point inside of the curve will be a

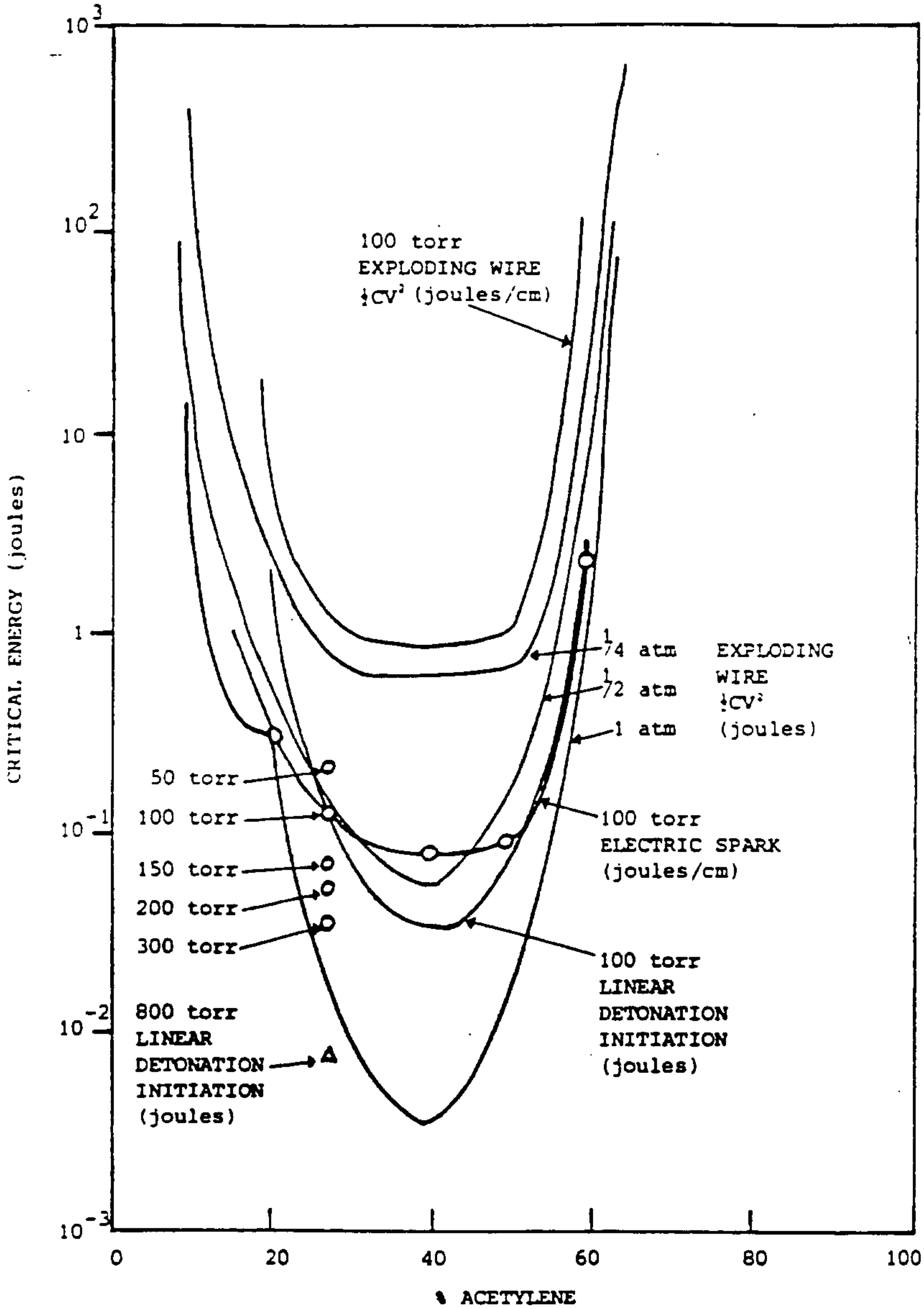


Figure 5.1 The dependence of the critical energy for direct initiation on mixture composition for C_2H_2-O_2

Figure 5.2 illustrates another set of typical detonation energy curves where the most detonable compositions occur at the slightly fuel rich side of the stoichiometric mixture. (Stoichiometry is expressed here as equivalence ratio being the ratio of fuel to oxygen divided by the fuel to oxygen ratio at stoichiometry).

From the above discussions on initiation and limits, one sees qualitatively the narrow limits generally found for unconfined spherical waves as compared to planar waves. Experiments have established that the average cell size is a constant for a self-sustained detonation. Thus, for a planar wave propagating in a tube, the total number of cells of the detonation front is, on the average, a constant. However, for diverging waves, the surface area of the front increases with radius. Thus, to keep the average cell dimenson the same, the total number of cells have to multiply continuously as the wave expands. This requires the formation of more than one localized explosion at the end of the cycle of a decaying blast wavelet. In this way the cell may divide to form more new cells. If multiplication does not occur in a diverging wave, the cell size gets progressively larger, and the increase in the time for the blast wavelet to decay means that the thermodynamic states at the end of the cycle, when the transverse waves finally collide, may drop below the autoignition limit required for localized explosion to occur. Hence, reinitiation is not possible, and the wave fails. A rule of thumb that appears successful suggests that a minimum FAE detonation energy is that which is liberated fom one or two percent of the fuel weight of TNT.

The delay time between the instant of FAE cloud dispersion and the ignition of the detonator is an important parameter. If the delay time is too short, the fuel will not have had time to break up into small enough drops to detonate. If the delay time is too long, the small drops in the micromist will have coalesced into larger drops which once again will not be detonable. Table 5.1 shows some figures for the upper limit time delay for propylene oxide.

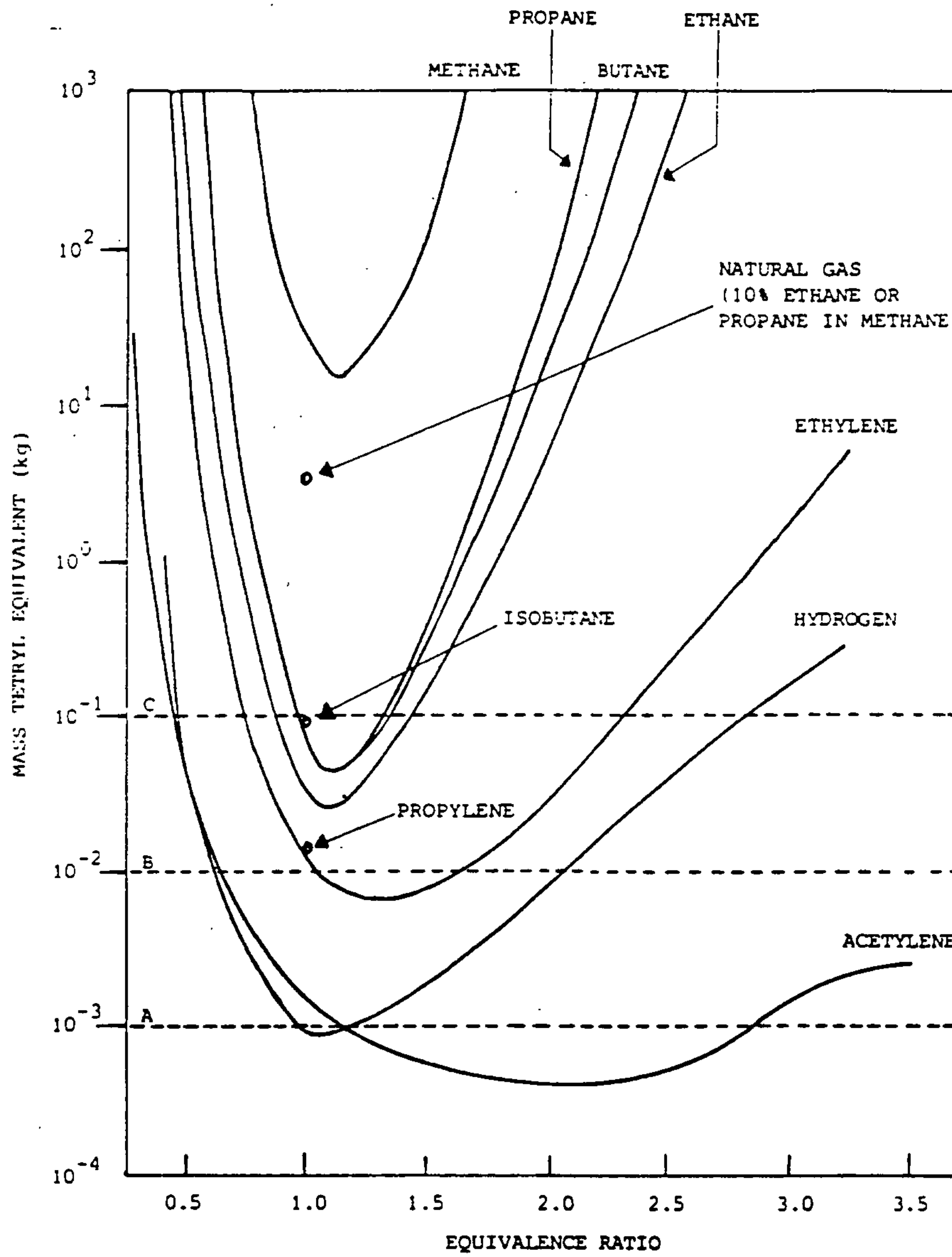


Figure 5.2 Detonability limits versus initiation energy for gaseous fuels in air

VARIATIONS IN DELAY TIME

(Propylene Oxide Fuel)

Delay Time (ms)	Detonation
40	Yes
60	Yes
120	Yes
180	Yes
210	No
240	No
360	No

TABLE 5.1

5.5 MULTIPLE CLOUDS AND MUTUAL DETONATION

As will be discussed later, there are some advantages in principle to dispersing a fixed weight of FAE fuel among several smaller clouds instead of in one large cloud. On the other hand, one of the problems is to achieve very nearly simultaneous detonation of each of the cloudlet detonators. If this is not achieved, the first FAE explosion may disperse the nearby cloudlets so much that they may no longer be of a detonable fuel air mixture by the time their detonators go off.

Although there is little in the literature on this subject, one researcher has successfully transferred the detonation of one cloudlet to another thereby avoiding the problem of synchronized multiple detonators.

The detonation transfer experiments involving two FAE clouds were performed for the purpose of determining the maximum allowable spacing between canisters and the maximum allowable cloud dwell (detonation delay) time. In this first series of experiments, the burster charges of each canister were detonated simultaneously. Each canister comprised 2 gallons of propylene oxide fuel with a length to diameter ratio, l/d, of two. Table 5.2 presents the various experiments performed and indicates whether or not the detonation transferred from one cloud to the other. For instance, with a 8.53m spacing between the canisters and a cloud dwell time of 120ms the detonation of one cloud did not cause the detonation of the second cloud.

DETONATION TRANSFER EXPERIMENTS
(2 gallon, l/d = 2, P.O. fuel)

Spacings, S (m)	Time Delay (ms)	Cloud-Cloud Detonation Transfer
8.53	120	No
7.32	120	Yes
7.32	120	No
6.71	90	Yes
6.71	160	Yes
7.92	160	No
7.32	160	Yes

TABLE 5.2

Representing the results of this set of experiments graphically, as in Figure 5.3, shows clearly that as the spacing between canisters is increased then more time for cloud dispersal must be allowed to ensure a successful cloud to cloud detonation transfer. Consequently for successful detonation transfer, cloudlet overlap is a requirement.

Following on from this research work another test involved the dissemination and detonation of a seven canister array. Each canister contained 3.18 kg (7 lbs) of propylene oxide. The length to diameter ratio ,l/d, of each of the canisters was 2 and the fuel to burster ratio, F/B, was 100. The canisters were placed in an array as shown in Figure 5.4. In this test the cloud dwell time was 100 msec and δt was 0, i.e., the

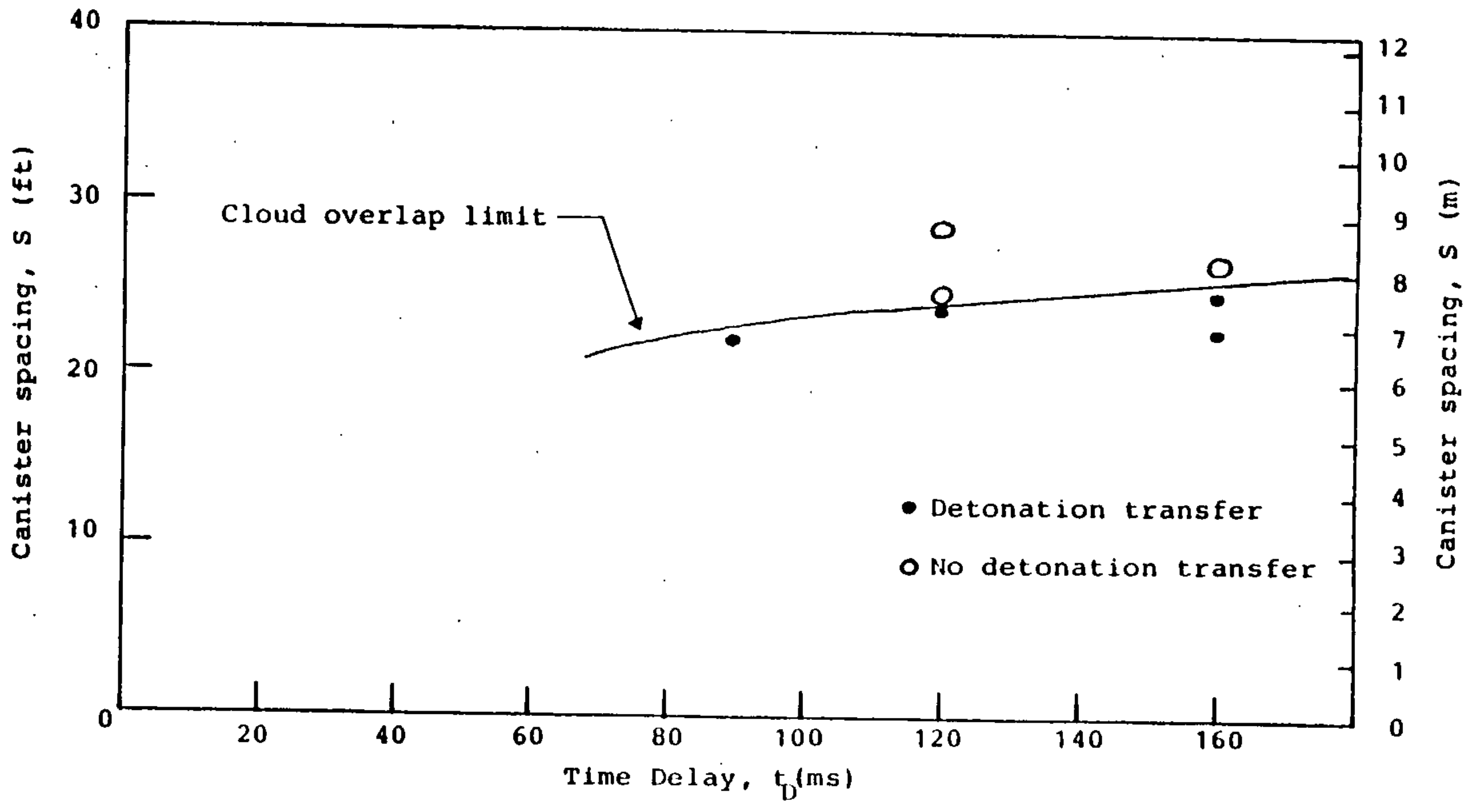


Figure 5.3 Results of detonation transfer experiments. Spacing, S, between canisters versus delay time, t_D, between burster initiation and cloud detonation. Propylene oxide fuel, 2 gallons, $l/d = 2$, $F/B = 90$.

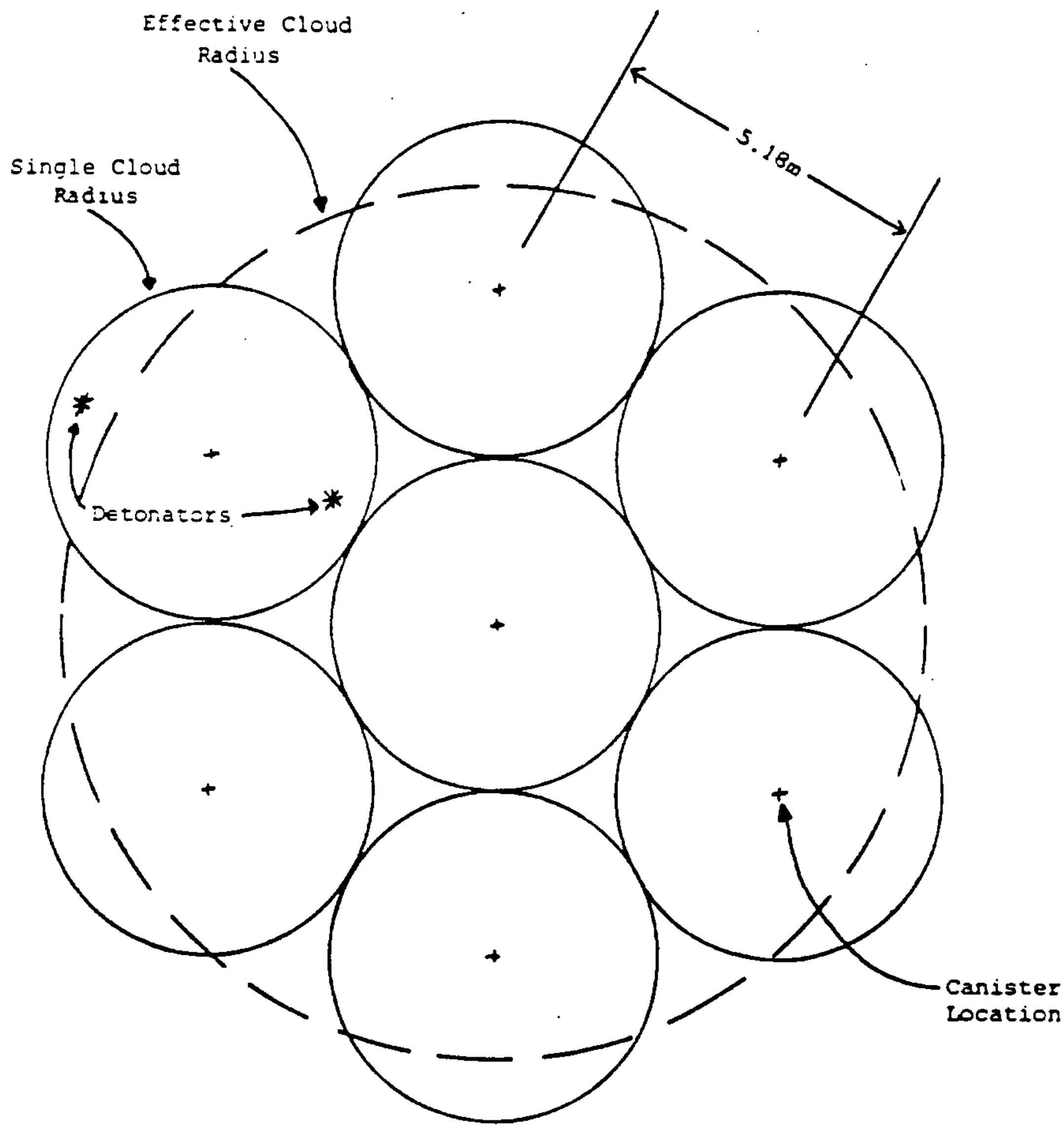


Figure 5.4 **Sketch showing the relative positioning of the individual canisters. The seven circles represent the FAE clouds from the**

burster charges in all of the containers were detonated simultaneously. Second event detonators were placed in only one of the clouds so that the ability of the detonation to transfer in this configuration could be determined. The results showed that detonation did indeed transfer throughout the multicloud array.

Table 5.3 shows the effect of lack of fuel dispersion simultaneity on detonation transfer efficiency. Not surprisingly when one of the cloudlets is old compared to the other there is less likelihood that the detonation will transfer.

5.6 SUMMARY

From the discussions in this section, the successful detonation of an FAE cloud depends on several factors including proper fuel air mixing, proper delay time and sufficient detonation energy. From the U shaped curves of Figure 5.1 and 5.2 exact stoichiometry is not necessary for successful detonation although the net explosive yield will be reduced by any deviation from stoichiometry.

We may conclude that a successful four hundred kilogram FAE warhead will probably be detonated by four kilograms of TNT about one hundred to two hundred milliseconds after the fuel is dispersed by the burster charge. Mutual detonation of multiple clouds looks feasible, but the advantages of multiple clouds are not clear at this time. This issue will be explored more fully in the final report. Chemical detonation is also an interesting possibility, but is so undeveloped that we do not recommend it at this point.

Fuel Mass (g)	Canister Spacing (m)	δt (ms)	t_D (ms)	γ*	Detonation Transfer
14	7.32	60	180	0.667	Yes
14	7.32	100	180	0.440	No
14	7.32	80	200	0.600	Yes
14	7.32	120	180	0.330	Partial
14	7.32	90	180	0.500	No

*γ is the age of second cloud divided by age of first cloud at time of cloud detonation. Single 100 gm Comp C-4 cloud detonator immersed in first cloud.

Table 5.3 Burster Delay, δt (P.O. Fuel)

6. BLAST

6.1 Background

In many engineering applications, the blast profiles of all explosives are treated identically. This is not surprising given the relatively crude uses to which they have been put. However, in recent decades the growing concern about the effects of nuclear weapons and a realization of the damage potential from natural gas and petrochemical explosions has generated many studies of specific blast phenomena that have revealed important differences between nuclear, fuel-air and conventional high explosive blast profiles. (See Figure 6.1).

The parameters of interest are energy released, time, distance from hypocentre, peak static and dynamic overpressure, and static and dynamic impulse. Numerous theoretical and emperical models exist relating these parameters for each class of explosion listed above. There also exist many models which allow one to compute approximate blast parameters of one class using the better understood processes of another class. For example, blast properties of the conventional high explosive, TNT, have been studied and understood in great detail so there are many models relating nuclear and FAE to TNT. Similarly, as FAE becomes better understood, more models relating FAE to nuclear blast parameters are being developed.

Scaling laws have also been developed and expanded which allow one to easily compute blast effects at a given distance for any blast yield when one knows the effects at one distance and yield. The most successful of these is the Hopkinson cube root scaling law.

The most significant differences between conventional high explosives and the others is that TNT and similar explosives produce very high peak overpressures from very nearly a point source, while nuclear and FAE produce peak overpressures over an extended region. Also the overpressure declines with distance much faster with conventional explosives than with nuclear and FAE. Accordingly, models developed for one class

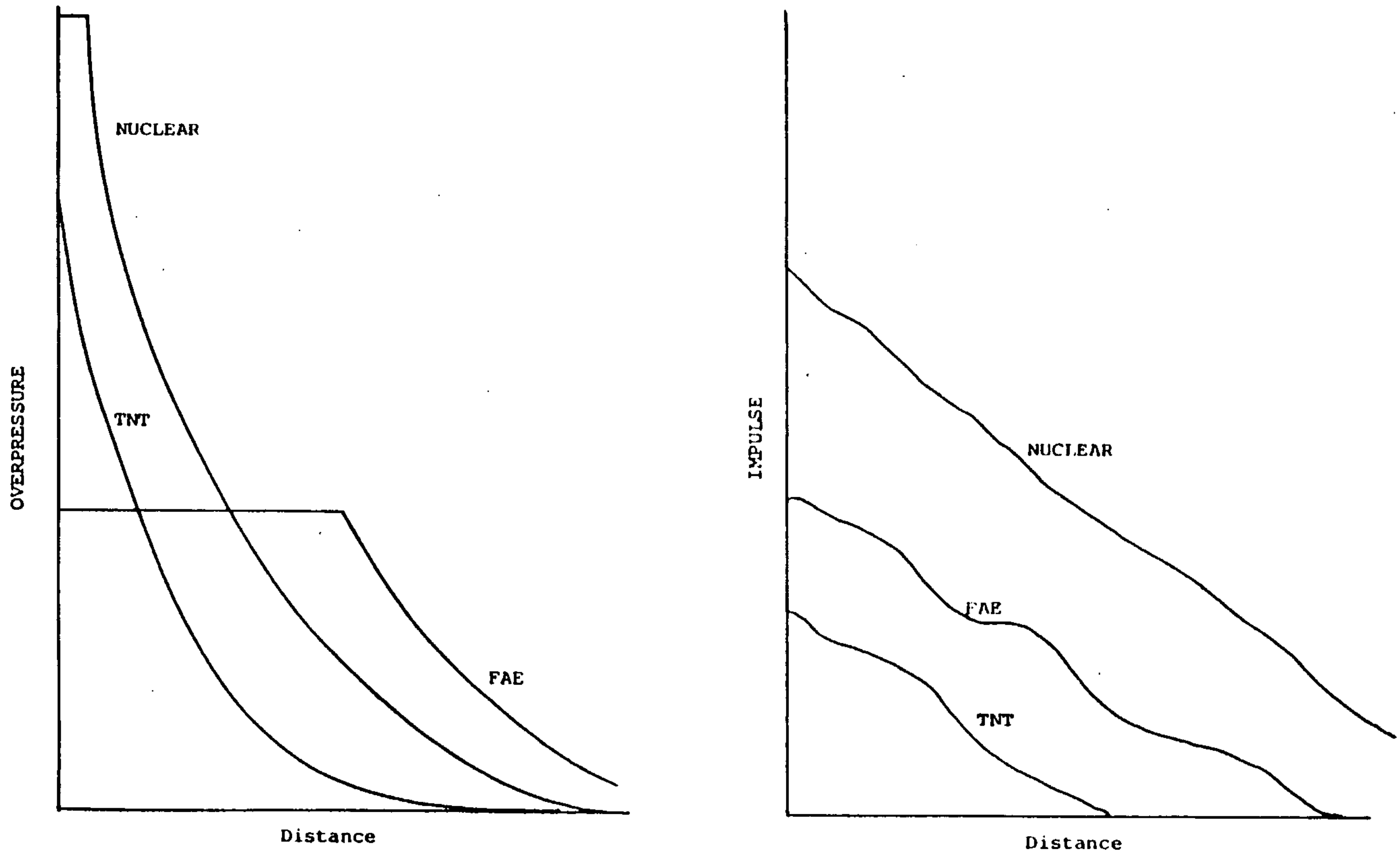


Figure 6.1 Qualitative comparison of blast parameters of convential, nuclear and FAE explosives of similar yield

of explosive have to be carefully adjusted prior to application to other classes. These adjustments typically are in response to the two blast regions apparent in the FAE overpressure curve in Figure 6.1 which are known as near field and far field. In far field most models are equivalent and effective. It is in the near field, in the flat overpressure region inside the cloud, that significant and important differences occur and where the usual scaling laws fail.

6.2 SCALING LAWS

Appropriate scaling laws can be applied in order to calculate the characteristic properties of the blast wave from an explosion of any given energy if those for another energy are known. With the aid of such laws it is possible to express the data for a large range of energies in a simple form.

Theoretically, a given pressure will occur at a distance from the point of detonation that is proportional to the cube root of the energy yield. Full-scale tests have shown this relationship between distance and energy yield to hold for yields over a very large range. Thus, cube root scaling may be applied with confidence over a wide range of explosion energies. According to this law, if D_1 is the distance from a reference explosion of W_1 units of energy at which a certain overpressure or dynamic pressure is attained, then for any explosion of W energy units these same pressures will occur at a distance D given by

$$\left(\frac{D}{D_1}\right) = \left(\frac{W}{W_1}\right)^{1/3}$$

Cube root scaling can also be applied to arrival time of the shock front, positive phase duration, and positive phase impulse, with the understanding that the distances concerned are themselves scaled according to the cube root law. The relationships may be expressed in the form

$$\left(\frac{t}{t_1}\right) = \left(\frac{D}{D_1}\right) = \left(\frac{W}{W_1}\right)^{1/3}$$

and $$\left(\frac{I}{I_1}\right) = \left(\frac{D}{D_1}\right) = \left(\frac{W}{W_1}\right)^{1/3}$$

where t_1 represents arrival time or positive phase duration,

I_1 is the positive phase impulse for a reference explosion of energy W_1,

t and I refer to any explosion of energy W, and

D_1 and D are distances from ground zero.

6.3 MODELS

6.3.1 Cloud Radius

Once the quantity of fuel is specified, the optimum cloud radius is determined by the combustion chemistry of the fuel, that is, the fuel must be spread over a volume just large enough so that oxygen in the air of that volume is just sufficient for complete combustion of the fuel.

Since the shape of the cloud will be roughly hemispherical or cylindrical, the radius will vary with the cube root of the volume. This is a very slowly varying function which means that although the volume will depend on the chemistry it will not change the radius much even with large chemistry changes from fuel to fuel. Accordingly, the principal control of cloud radius will be by fuel quantity.

For the fuels listed in Table 3.4 and a warhead mass limited to 400 kilograms, a single FAE cloud will have a radius on the order of ten to fifteen metres. An analytical expression for this will be presented in the final report.

6.3.2 Strelow Model (TNT)

Many existing guidelines for estimating blast damages from chemical explosions are based on the TNT equivalent yield concept. If W_F grams of a certain fuel is released into the atmosphere and H is the standard heat of combustion of this fuel in calories/gram, then the TNT equivalent yield is

$$W_{TNT} = \frac{\alpha \Delta H \times W_F}{1120} \qquad (6.3\text{-}1)$$

where α is some empirical factor ($0 < \alpha < 1$) and

1120 is the explosion energy of TNT in calories/gram.

Once W_{TNT} is found, a characteristic explosion length R_o defined by

$$R_o = \frac{(W_{TNT} \times 1120)^{1/3}}{P_o} \qquad (6.3\text{-}2)$$

can be calculated. In Equation 6.3-2, W_{TNT} is in grams and P_o is the pressure of the atmosphere in Newton/cm^2 at sea level.

With R_o determined, a standard chart yields the blast overpressure Δps and the impulse I with the scaled distance. This method assumes that the blast from a vapour cloud explosion in which a mass of fuel W_F is released into the atmosphere is equivalent to that from the detonation of a concentrated charge of TNT of mass W_{TNT}.

The empirical factor α in Equation 6.3-1 is used to account for all the differences between both types of explosions. From the reconstruction of past accidents, it is found that α can vary from an insignificant fraction of a percent to values as high as 30%. Even if an adequate value of α were known, the blast wave decay from both types of explosion can only be similar in the far field. In the near field, the blast from a TNT explosion is much stronger and yields much higher blast overpressures than the corresponding values for practically all fuel air vapour cloud explosions.

It has long been recognized that the TNT equivalent method can yield a very crude estimate. However, due to the large number of unknown factors in most FAE releases it may be argued that they completely overshadow the inadequacies of the TNT equivalent method.

6.3.3 Brode Model (Nuclear)

The original Brode model was developed for conventional high explosives that more nearly fit the idealized case of a point source explosion. The peak overpressure Δps at high pressure is

$$\Delta ps = 0.1567r^{-3} + 1 \text{ atmos.}$$

The shock radius (r) is in dimensionless units of energy/pressure. At lower pressures the emperical equation below applies

$$\Delta ps = \frac{0.137}{r^3} + \frac{0.119}{r^2} + \frac{0.269}{r} - 0.019 \text{ atmos.}$$

for $0.1 < \Delta ps < 10$ or $0.26 < r < 0.28$

The modified Brode model for nuclear blast simulation may be expressed as follows where P is in psig,

$$P(r,W) = \frac{1.58W}{r^3} + 5.4\left(\frac{W}{r^3}\right)^{1/2} + 0.0215 \qquad (6.3\text{-}3)$$

and r is in thousands of feet and W is in kilotons equivalent yield.

It should be pointed out that W in Equation 6.3-3 is for an equivalent nuclear detonation. But only 50% of the nuclear energy release goes into the blast (with 30% and 40% going into heat and the remainder into nuclear radiation). Consequently, $W/2 = W_o$ where W_o is the total equivalent weight in FAE fuel. However, FAE fuels are k times more energetic than TNT so we get $W/2 = kW_o$, where k is the energy of explosion (Table 3.4) divided by 1120. Further, the combustion efficiency, f, of FAE fuels is low in the range of 5% to 30%, and so we have $W = 2kfW_o$. Substituting this into Equation 6.3-3 gives:

$$P(r,k,f,W_o) = \frac{3.16kfW_o}{r^3} + 7.6\left(\frac{kfW_o}{r^3}\right)^{1/2} + 0.0215 \quad (6.3\text{-}4)$$

This model approximates the FAE case if one truncates the overpressure at 260 psig which is the peak overpressure within the FAE blast cloud for most fuels.

6.3.4 Dow, Sedov, and Kogarko Models (FAE)

The Dow approximation is perhaps the least satisfactory since it does nothing more than modify the TNT model.

$$W_e = 0.23W\ \Delta H_e f \qquad (6.3\text{-}5)$$

where W_e is the TNT equivalent energy in the FAE cloud expressed in grams,
ΔH_e is the net heat of combustion of the released material in btu/lb,
f is an energy yield factor and
W is the weight of the FAE fuel in pounds.

Substituting Equation 6.3-5 into W_{TNT} of Equation 6.3-2 and truncating the pressure at 260 psig, we arrive at the Dow approximation,

$$R_o = \frac{6.34}{P_o}(W\Delta H_e f)^{1/3}$$

which can be solved for overpressure using the same charts as Strelow.

The Sedov model takes into account the geometry of the cloud through the terms ν and α as well as the source energy E_o and the range r in metres:

$$P = \frac{1.9 \times 10^{-4}E}{(\nu+2)^2(\gamma+1)r^{\nu}}$$

where, $E = E_0/\alpha$,

P is the peak overpressure in Newtons/cm^2, and

γ is the specific heat ratio for air = 1.4.

Table 6.1 gives the geometry dependent values for ν and α.

FAE Cloud Geometry	ν	α
Plane	1	1.075
Cylindrical	2	1.000
Spherical	3	0.850

TABLE 6.1 Cloud Geometry

The Kogarko model is also empirically derived, and like the others is truncated at 377 Ncm^{-2} (260 psig) to account for the near field overpressure within the FAE cloud. Peak overpressure, P, in Newtons/cm^2 is

$$P = \frac{0.51}{R^{1.7}} \qquad \text{for } 0.08 \leq R \leq 0.3$$

and

$$P = \frac{0.0061}{R} + \frac{0.0015}{R^2} + \frac{0.00026}{R^3} \qquad \text{for } R > 0.3$$

where $R = rW^{-1/3}$ and

r is range in metres from the blast hypocentre and

W is total combustion energy in kilocalories.

6.4 OVERPRESSURE COMPUTATIONS

Typical overpressure curves for propane are shown in Figure 6.2 for the Kogarko model as well as for the modified Brode model. The cases shown are for a 0.8 cubic metre volume limited payload (V) and a 400 kilogram mass limited payload (M).

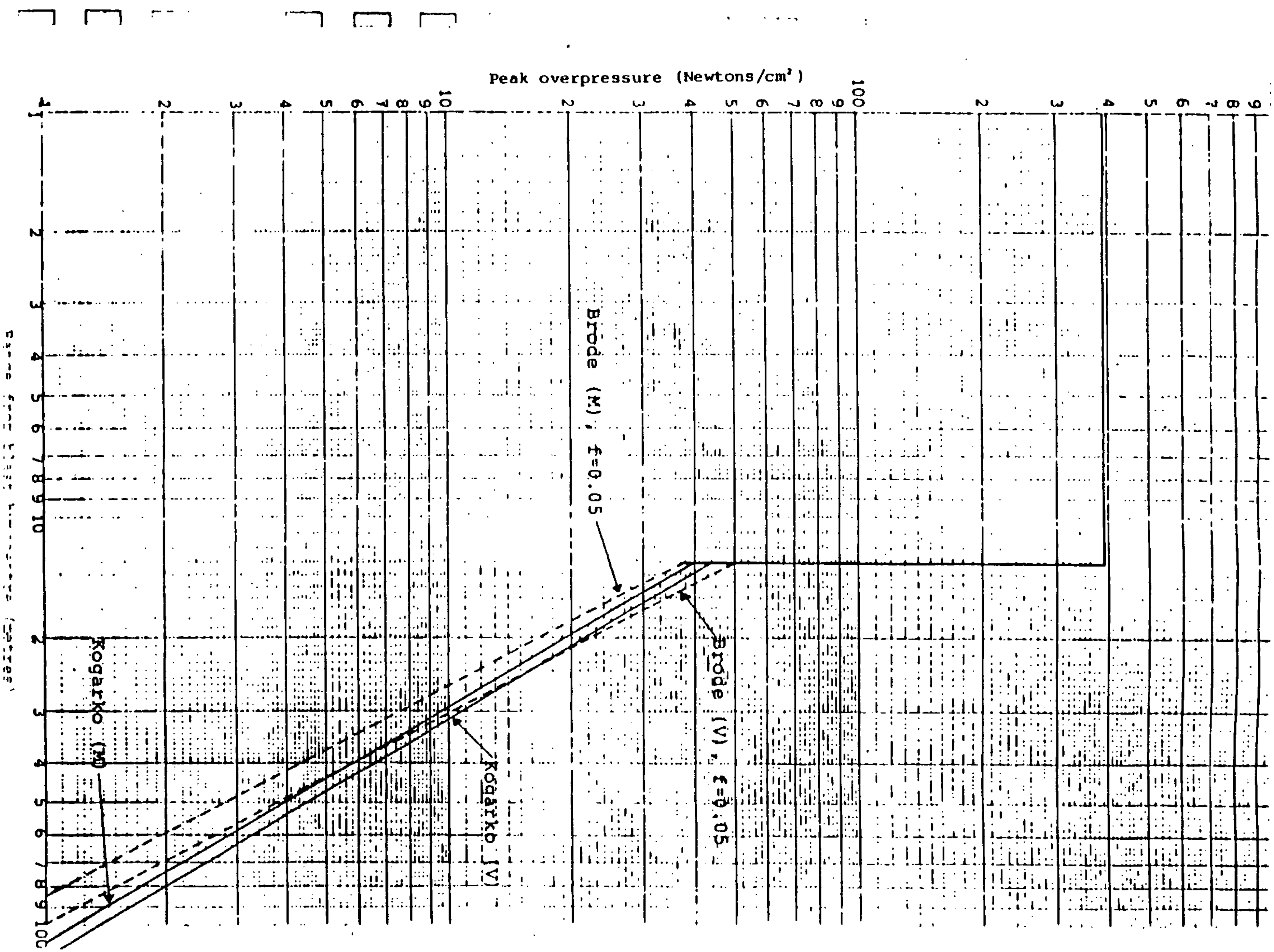
A combustion efficiency (f) of 5% was assumed with the Brode model.

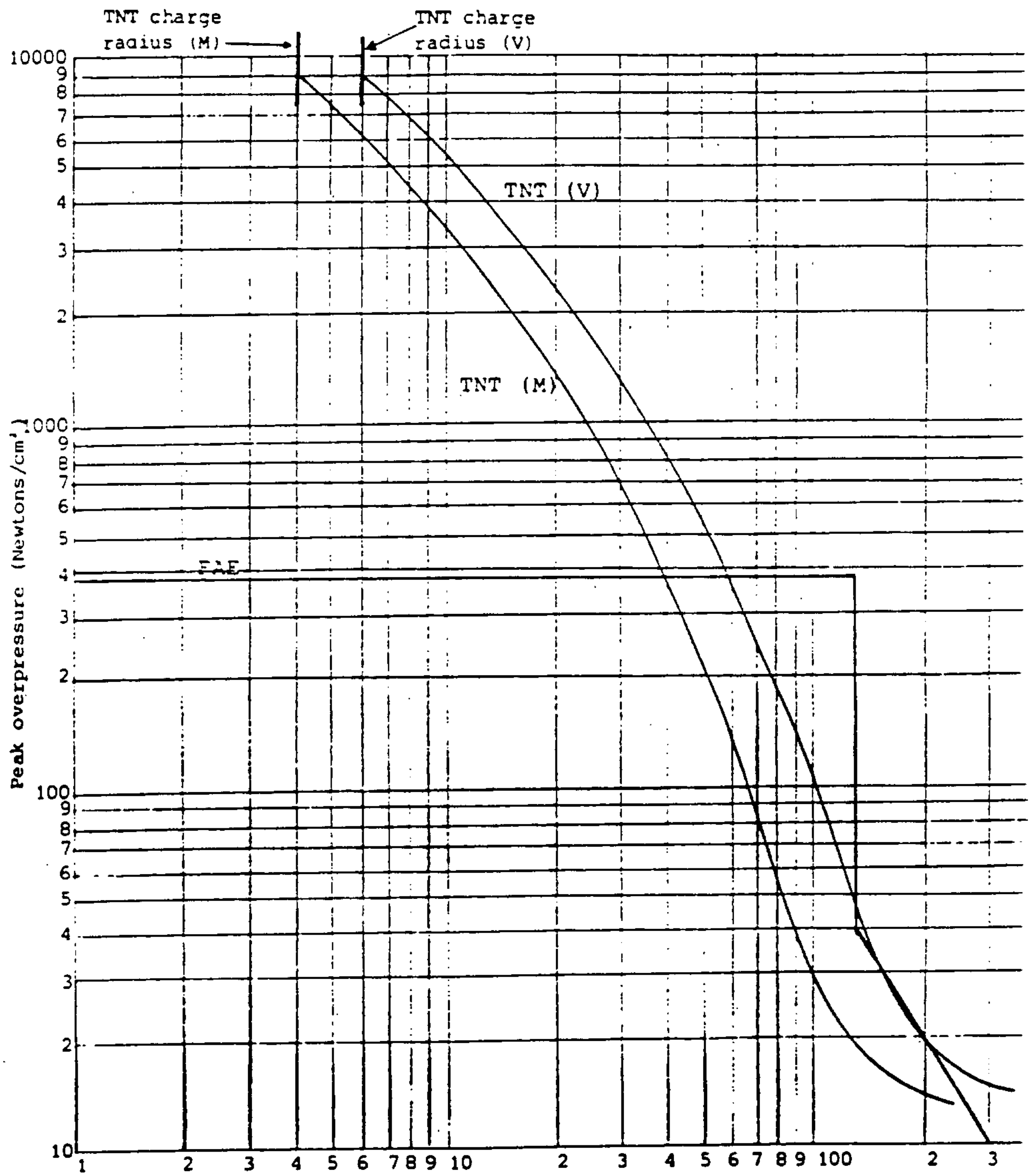
It is interesting to note that there is relatively little difference between the mass limited case and the volume limited case, indeed the differences are smaller than the model to model differences.

In Figure 6.3 the Kogarko model is plotted with a TNT curve for both the mass and volume limited cases. The characteristically higher overpressures in the near field for TNT are evident as well as the similarity of models in the far field where TNT and FAE are about the same.

On the basis of a preliminary evaluation of the several models considered here, we conclude that the modified Brode and Kogarko models are the most suitable and give comparable results. The Brode model is quite sensitive to the assumed value of f which is not very well known, and can vary from blast to blast. Accordingly, it may be prudent to use this model with a range of f values.

The Kogarko model is empirically derived directly from experiments so is intrinsically more representative of the weapon system we are considering. Our plan is to further evaluate the different models and present blast overpressure curves for all fuels in Table 3.4 for the best model.


Peak overpressure (Newtons/cm²)
Brode (M), f=0.05
Brode (V), f=0.05
Kogarko (M)
Kogarko (V)



TNT charge radius (M)
TNT charge radius (V)
TNT (V)
TNT (M)
FAE
Peak overpressure (Newtons/cm²)

6.5 SUMMARY

The FAE cloud radius and hence the area of peak overpressure will be determined primarily by the quantity of fuel and to a lesser extent by its combustion chemistry. In all cases for the system at hand the radius will be between ten and fifteen metres.

Scaling laws have been presented which allow one to predict peak overpressure in the far field as a function of the cube root of the energy yield.

Five blast models have been examined and two (Brode and Kogarko) selected for further consideration. The overpressure predictions for both are consistent with each other. Using propane as a typical fuel, we find a peak overpressure within the fuel cloud of 377 N/cm^2 (260 psig) and an overpressure with the specified warhead high enough to damage some structures 60 to 80 metres from the blast hypocentre.

7. INTRODUCTION

When assessing the effectiveness of a FAE system it is necessary to know the effect of blast on the likely targets. The targets of interest for the FAE payload are, not in any order of priority;

- Airbases
- Towns and Cities
- Oil refineries
- Naval Ports

Each of which can be classified as "soft" area targets made up of smaller target arrays of different types with differing degrees of resilience to attacks. For example, the airbase target, as illustrated at Figure 7.1 is made up of a number of individual target types;

- The operating strip(s)
- Hangers
- Maintenance/Support Buildings
- Aircraft in the open
- Aircraft in revetments
- Aircraft in reinforced bunkers
- Vehicles
- Personnel

Not all of these target types will be susceptible to attack from FAE-type warheads. For example, the operating strip and aircraft in reinforced bunkers where cratering or penetration-type warheads will be required. The vulnerability of each target-type to FAE attacks will be quantified in the final report. However, investigations into this area have already started.

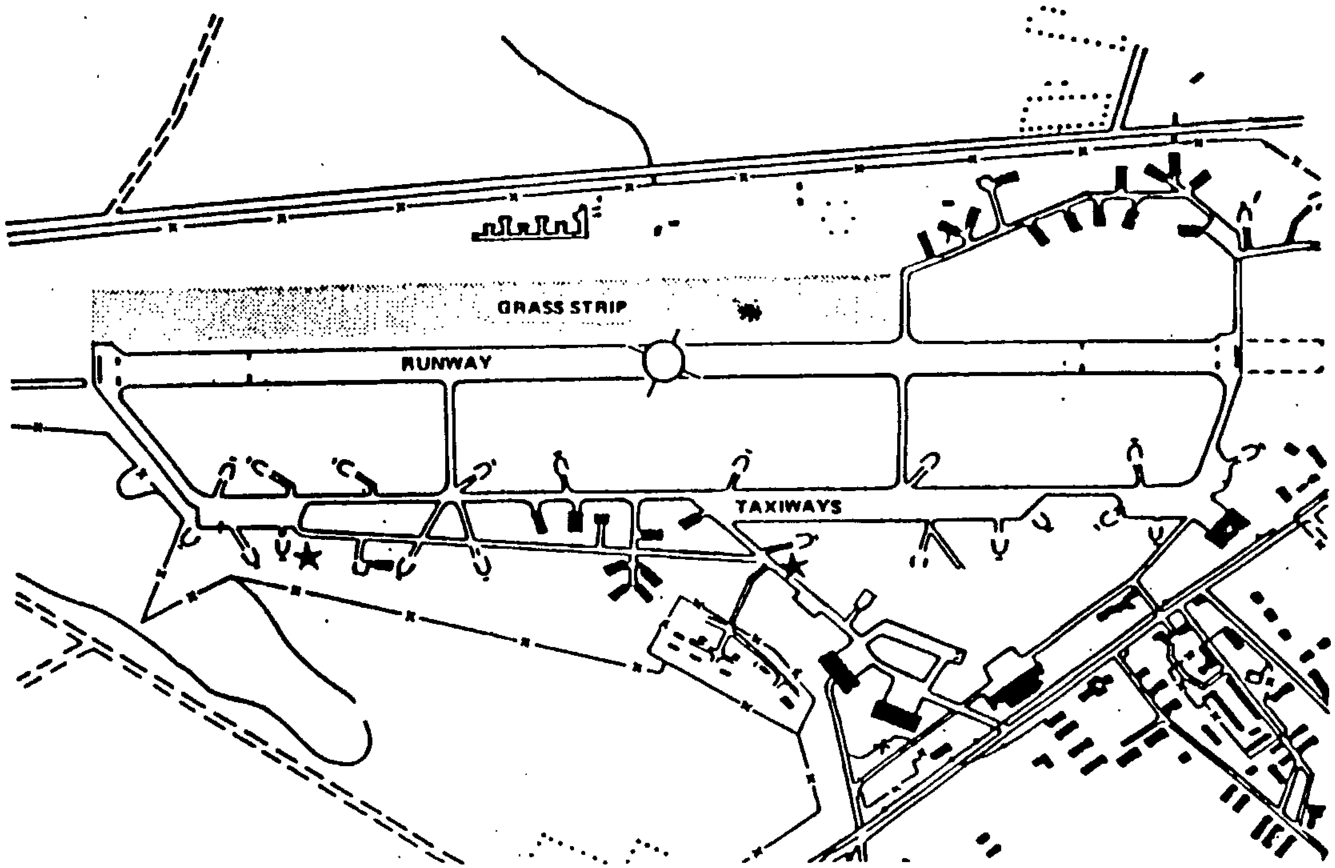


Figure 7.1 Typical aerodrome layout

7.2 RESPONSE OF PERSONNEL

Considerable research on the effects of blast on personnel has been carried out and the two main centres of work are in Sweden (National Defence Research Institute) and USA (Lovelace Biomedical and Environmental Research Institute). Trials have been conducted on animals to assess the effect of blast on wing tissue and also using an anthropomorphic dummy developed in Sweden. The incidence of blast injuries in Northern Ireland, UK has led to a number of reports[119-121] and reviews of this area have also been published[122-123].

7.3 RESPONSE OF STRUCTURES

The effect on structures is much harder to predict than that on personnel due to complex geometries giving blast wave reflections and that often it is the blast impulse (i.e. the area under the positive portion of the pressure-time curve) rather than simple overpressure which is the critical factor. For minefield clearance both pressure and impulse have to reach certain levels before activation of many mines. FAE are useful as blast weapons not only because detonation pressures are exerted over large areas but also because the blast wave outside the cloud decays more slowly than HE giving rise to higher blast impulses. In addition a vapour cloud can be delivered or drawn into the interior of structures and detonated which is very effective in demolition of soft structures or, in the case of hard targets, such as command centres, kill personnel whilst leaving such a structure intact.

The analysis of structural response to blast loading is essentially via an idealisation of the system into a lumped mass-spring system where the structure of a calculated equivalent mass is supported by a spring of stiffness equivalent to the structured stiffness. This system is loaded by an idealised load equivalent to the blast loading pulse. This approach was first developed at MIT and still forms the basis for design of reinforced concrete and structural steel

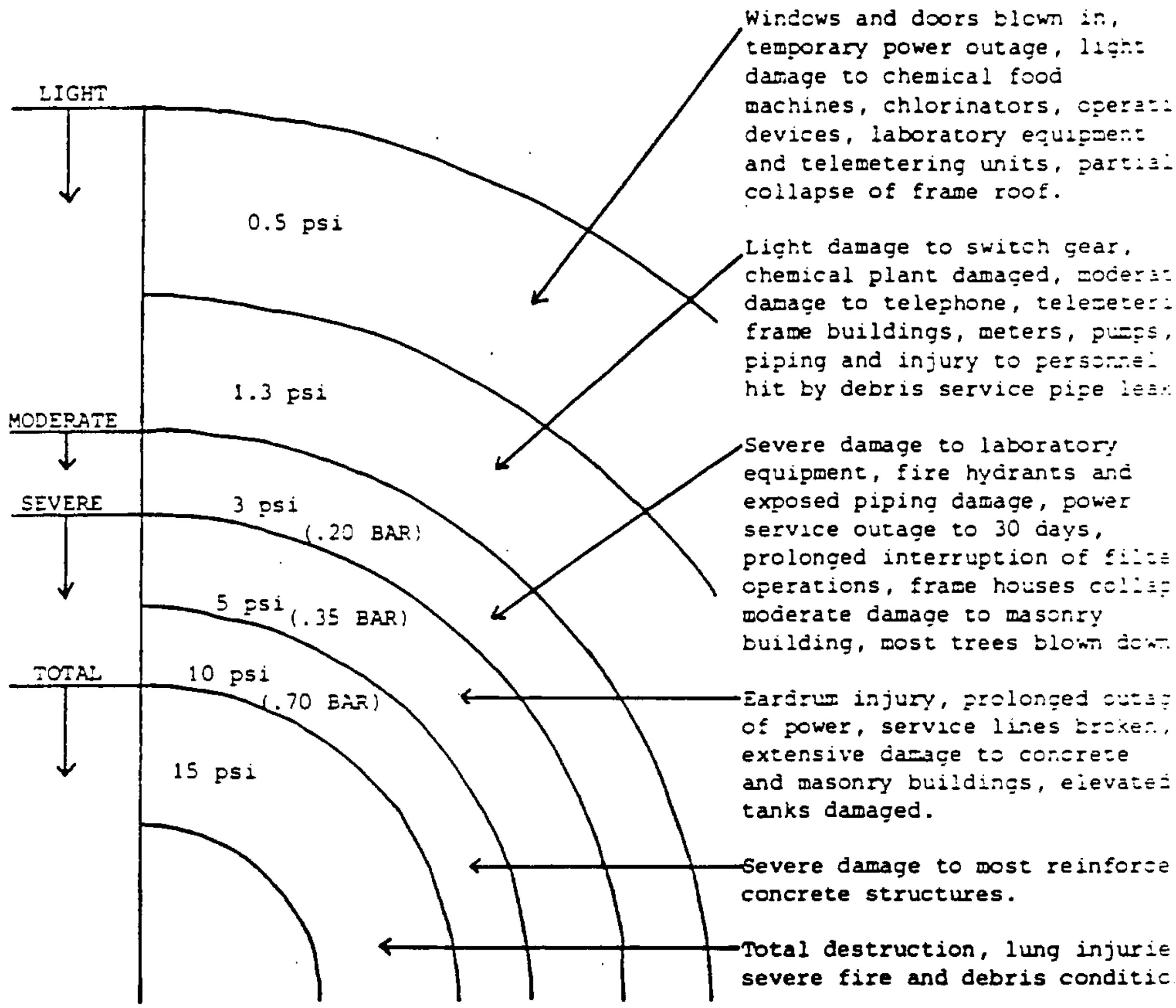


Figure 7.2 Overpressure damage to structures and personnel

Vulnerability of Personnel and Structures

Target	Overpressure (bar)	Effects
Personnel	> 0.1	Ear drum damage
	> 0.7	Lung damage
	2.0	Lethal threshold
	3.0	50% fatalities
	6.0	100% fatalities
Structures (Vehicles)	> 0.1	Windows broken
	0.3	Minor damage
	1.5	Major structural damage

TABLE 7.1

7.5 RESPONSE OF AIRCRAFT AND SHIPS

The vulnerability of aircraft and ships is an important factor when considering the lethality of FAE weapon systems. Table 7.2 was drawn up with data available from reference 20.

Vulnerability of Aircraft and Ships

Target	Pressure peak (Kp/cm^2)	Effects
Parked aircraft	0.28 to 0.42	Completely destroyed
Ships	0.42 to 0.7	Medium damage (Defeats navigational equipment and machinery, forcing extensive repair work)
	0.7 to 0.85	All types of ships badly damaged or sunk
	In excess of 0.9	Sinking

TABLE 7.2

7.6 SUMMARY

In this section we have considered three references for the provision of target vulnerability data due to blast overpressure.

The vulnerability data from these references has been presented for targets of personnel, vehicles, structures, aircraft and ships.

By comparing the three sources of information it is clear that different assumptions have been made in presenting the vulnerability data. In completing the final part of the study, a deeper understanding of these assumptions will be made with a view to producing a single set of vulnerability pressures for the targets of interest.

This information will then be used in the assessment and effectiveness work discussed in the following section.

8. ASSESSMENT/EFFECTIVENESS STUDIES

8.1 INTRODUCTION

This section of the interim report describes the methodology to be used for assessing the optimum design of FAE warhead and the most cost effective solution for the targets of interest.

8.2 METHODOLOGY

The overall assessment scheme is shown in block diagram form in Figure 8.1. The two primary outputs will be;

- o Payload optimization/design
- o Payload selection based on cost effectiveness

8.3 PAYLOAD OPTIMIZATION/DESIGN

Any single payload design will have a specific combination of;

- o Fuel type
- o Volume/Mass
- o Dispersion mechanism
- o Detonation Device(s)

Previous sections of this report have described the basis for predicting the payload performance in terms of overpressure as a function of range and time. It is possible therefore to define, for a given payload design, a lethal area over which the blast effects generated by the FAE warhead are equal to or in excess of the target defeat criterion.

To illustrate this point consider the effects of blast overpressure on a particular type of target to be specified according to the relationship defined at Table 8.1. Three levels of overpressure A,B and C will achieve 10%, 50% and 100% damage against the target respectively. Against each of these damage levels (or defeat criteria) the payload design can be optimized i.e. through variations in dispersion and detonation

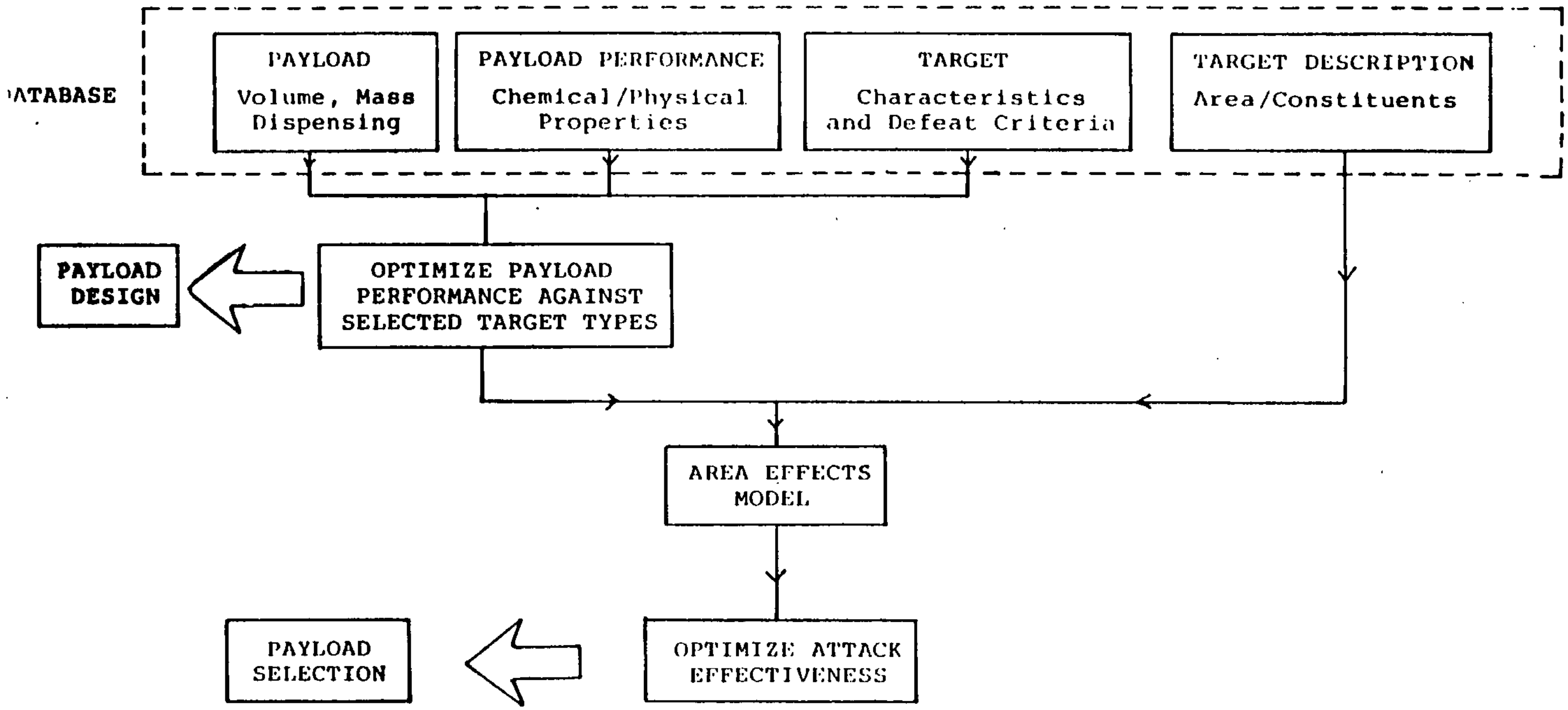


Figure 8.1 Assessment Methodology

Blast Overpressure	Effects
A	10% Damage
B	50% Damage
C	100% Damage

Table 8.1 Defeat Criteria

parameters to produce a range of effects as illustrated in Figure 8.2. Payload lethality can therefore be represented as circles which correspond to the different defeat criteria limits.

A specified defeat criteria can then be used to optimize and calculate lethal areas for each of the fuel types considered.

8.4 PAYLOAD SELECTION

It will be necessary to assess the effects of the different payload designs against representative target descriptions before selecting the most cost-effective design.

An area-effects model has been developed to address the particular needs of the study. A description of this model can best be provided with reference to its main features, namely;

- o Delivery Errors
- o Payload Effectiveness
- o Target Characteristics
- o Model Results/Output

8.4.1 Delivery Errors

Missile delivery errors with respect to nominal aim/impact point are sampled from normal distributions which are characteristic of the missile's range and azimuth errors as a function of range.

8.4.2 Payload Effectiveness

Payload effectiveness, in terms of a lethal area with respect to a specified defeat criterion, is derived as an output from the first phase of the assessment where payload optimization is considered.

8.4.3 Target Characteristics

Complex targets such as the airbase depicted at Figure 7.1 can be represented as a number of rectangles which enclose the targets of interest i.e. the aircraft shelters and hangers. Each rectangle can then be described as containing a number of target types, with different defeat criteria.

8.4.4 Model Results/Output

Typically the results of one run-through of the model, where six payloads might be used against one target area, might be represented graphically as in Figure 8.3.

If the circles shown were lethal areas corresponding to all the target area the proportion of the target defeated would depend on the number of missiles delivered. The form of this relationship would be as illustrated in Figure 8.4.

Different payload concepts will have different lethal areas for the same defeat criterion and as the area increases (r_1 to r_3) the effect seen in Figure 8.4 will occur i.e. a smaller number of missiles required to achieve the same damage level or a higher degree of damage achieved through use of the same number of missiles. Alternatively, a single payload could be attributed a number of lethal areas corresponding to different defeat criteria and as the overpressure increases (P_1 to P_3) a smaller proportion of the overall target area is defeated.

Relationships of this type will be defined in order to determine the most cost-effective design of FAE payload against the range of targets of interest.

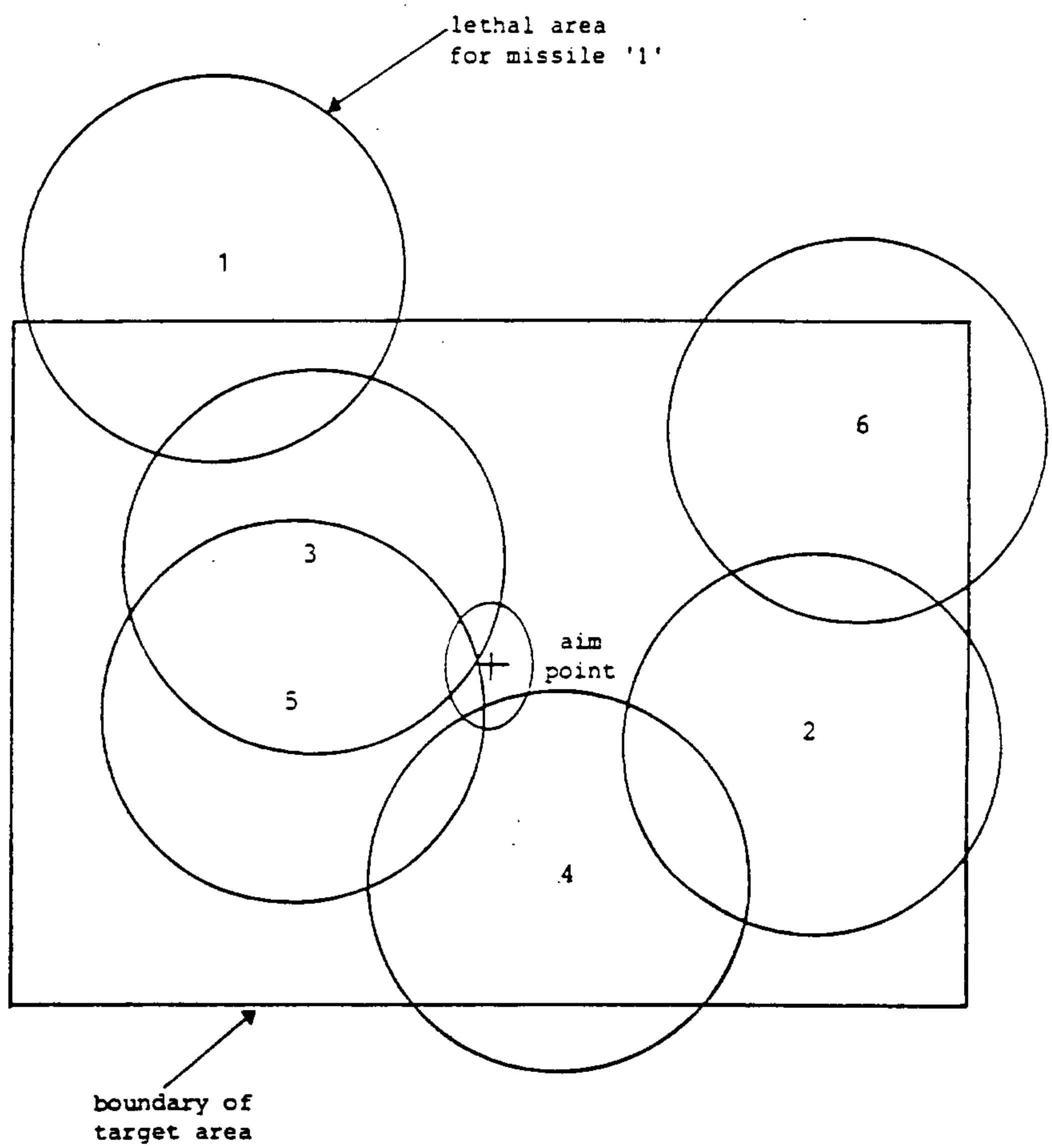


Figure 8.3
Graphical representation of attack by six missiles

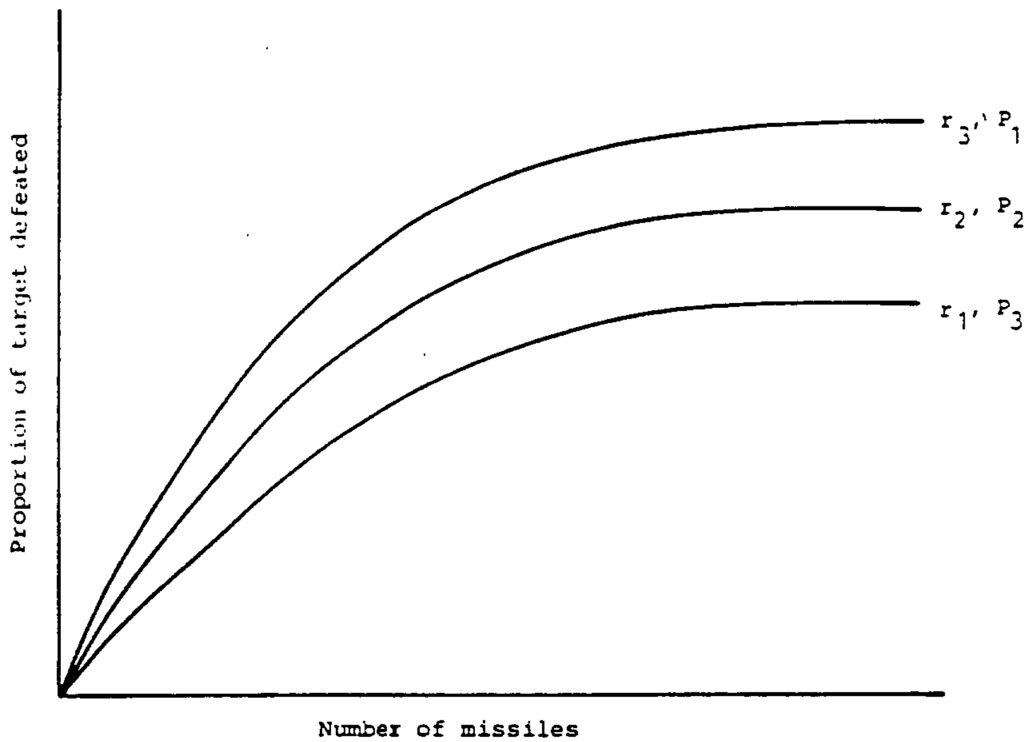


Figure 8.4 Proportion of target defeated as a function of the number of missiles delivered

8.5 SUMMARY

This section has described the considerations necessary for the final selection of the most preferable FAE warhead. A list of preferable FAE payload options will be presented to allow selection by consideration of both optimization/design and effectiveness. The bulk of this work is to be presented for the final report, drawing upon the recommendations of the work described in the earlier sections of this report.

9. MID STUDY CONCLUSIONS

Obviously at this point in the study not all views on the topics discussed are firm and final. However, it is possible to express current views on those items considered so far.

From an appreciation of the open literature on the subject it does not appear that any new FAE weapon system is under development at the present time. However, it is evident that the U.S. Government are continuing to support research into the subject.

Identification of feasible fuels has been made with a consideration of availability, handling, viscosity, ease of detonation and energy yield. With regard to detonation, the important aspects which are necessary to consider have been discussed in the main test and include fuel air mixing, stoichiometry, delay time and detonation energy. A selection of models which represent the effects of blast have been examined with two selected for further consideration. No preference for a unitary or multiple warhead can be demonstrated at the present time. These and further considerations will be made for the final report.

Several sources of information discussing target vulnerability have been identified and presented. The assumptions underlying these different sources will be identified with the aim of presenting a unique unified structure of defeat criteria for the critical targets necessary for the effectiveness assessment in the final report.

8.5 SUMMARY

This section has described the considerations necessary for the final selection of the most preferable FAE warhead. A list of preferable FAE payload options will be presented to allow selection by consideration of both optimization/design and effectiveness. The bulk of this work is to be presented for the final report, drawing upon the recommendations of the work described in the earlier sections of this report.

The assessment methodology for selection of the most preferable warhead has been discussed. An area effects model has been developed to address the particular requirements of the study. This model represents the final ballistic delivery aspects, the payload lethality and target vulnerability to give a systems appreciation and assessment capability for the range of fuels and target types considered. The input to the model is generated by the work of the earlier sections of this report.

At this point in the study a 400 kg FAE warhead comprising kerosine, with a 4 kg TNT detonation charge and a 100 ms to 200 ms delay time is a worthwhile consideration. However, it should be appreciated that this does not make any account for target vulnerability or the systems assessment work to be done.

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E S A INFORMATION RETRIEVAL SERVICE

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SEARCH HISTORY

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1	4209	EXPLOSIVES
2	495	FUEL(W)AIR
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PRINT SUMMARY

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1	6	3	4	1-77

RCH TIME 2.05 PRINT COUNT 77 DESCS.: 3

AD-A139 610/9 NTIS 84049611
Minimum Nonpropagation Distance for the Cloud Detonator of the XM130 SLUFAE Rocket
Stirrat, W. M.
Army Armament Research and Development Center, Dover, NJ. Large Caliber Weapon Systems Lab.*Shared Bibliographic Input (078533002 410163)
Final rept. Nov 82-Oct 83, Rept no: ARLCD-TR-83056, Feb 84, 43p, Monitor: SBI-AD-E401-137, NTIS Prices: PC A03/MF A01

As part of an Army-wide expansion and modernization program, safe separation distance criteria for the cloud detonator of the XM130 SLUFAE rocket and its assembly table were determined after study and testing. Two test series were involved: (1) a standard nonpropagation series for present table spacing of the detonators and the use on future conveyor systems, and (2) a series of structural integrity tests to determine the adequacy of the intrastation partitions. These tests established and statistically confirmed that a 122 cm (48 in.) free-air spacing between detonators would yield a 7.11% probability of propagation at the 95% confidence level; also, that the 1.27 cm (0.5 in.) thick steel wall between the work stations of the assembly table is sufficient to protect adjacent operators from accidental detonation fragments

Fld: 19A, 13L, 19G, 79A
Controlled terms: *Safety / *Detonators / *Structural properties / *Fuel air explosives / *Rockets / Plastic bonded explosives / Conveyors / Range(Distance) / Surface launched / Thick walls / Assembly / Separation / Test methods
Uncontrolled terms: SLUFAE(Surface Launched Unit Fuel Air Explosive) / PBXN-5 explosive / Cloud detonators / MMT(Manufacturing Methods and Technology) / XM-30 rockets / NTISDODXA

AD-A135 012/9 NTIS 84012307
Fuel-Air Explosive Simulation of Far-Field Nuclear Airblasts
Pierce, T. H.; Sedgwick, R. T.
S-Cubed, La Jolla, CA.*Defense Nuclear Agency, Washington, DC.*Shared Bibliographic Input (076234000 396528)
Final rept. 9 May 77-31 Dec 79, Rept no: SSS-R-80-4366, 31 Dec 79, 242p, Contract: DNA001-77-C-0251, Project: Y99QAXS, Task: D077, Monitor: SBI-AD-E301-256, NTIS Prices: PC A11/MF A01

Fuel-air explosions (FAE) have been investigated in the context of far-field nuclear airblast simulation. The objective of the investigation is to determine the feasibility of a reusable FAE simulator at the one kiloton level. Two issues have been researched in parallel efforts. These are the mechanisms by which largescale FAE clouds of controlled shape can be reliably and repeatedly formed and detonated, and the quality of nuclear airblast simulation that is achieved when such FAE clouds are detonated. The formation of hemispherical clouds by simultaneous, impulsive liquid fuel injection through a large number of radially directed, centrally clustered nozzles is discussed in detail. Specific fuel dispenser designs are considered and use experience with two of these is described. Survey experiments dealing with the atomization and penetration characteristics of large-diameter, impulsively formed single liquid jets are discussed. Small-scale hemispherical cloud formation experiments are also discussed. A new reusable facility for testing FAE simulation of nuclear airblasts at the 1/4-ton scale is described. Preliminary surface-burst experiments at that scale using propylene oxide and heptane as fuels are discussed. The results from these experiments are scaled and compared with 1 kt nuclear curvefits. The agreement is judged to be reasonable at this scale. Numerical calculations of the airblast that emerges from a detonated heptane-air cloud have also been carried out

FLD: 19D, 18C, 14B, 79E, 77D
Controlled terms: *Blast waves / *Nuclear explosion simulation / *Fuel air explosives / Blast loads / Clouds / Fuel nozzles / Liquid jets / Fuel systems / Simulators / Reusable equipment / Scale models / Fuel injection / Heptanes / Overpressure / Nuclear explosions / Far field / Reproducibility
Uncontrolled terms: Airblast / Blast Simulation / Propylene oxide / NTISDODXA / NTISDODSD

AD-A134 029/9 NTIS 84007693
Computer Program for Internal Aluminum-Fuel-Air Explosions
Reinhardt, Richard A.
Naval Weapons Center, China Lake, CA.*Shared Bibliographic Input (
020165000 403019)
Final rept, Rept no: NWC-TP-6449, Aug 83, 34p, Project: F32300, Task: WF32300000, Monitor: SBI-AD-E900-270, NTIS Prices: PC A03/MF A01

This report documents the internal explosion computer program INAL, used to calculate overpressures, temperatures, and chemical species present in the internal explosion of aluminized fuels in air. A complete listing of the program in HP-BASIC is presented, as well as a discussion of the function performed in each major subroutine

Fld: 19C, 19A, 9B, 79E, 79A
Controlled terms: *Aluminum / *Fuel air explosives / *Explosions / *Blast / Overpressure / Adiabatic conditions / Computer programs
Uncontrolled terms: Aluminized fuel / Internal explosions / Internal blast / NTISDODXA

AD-A133 505/9 NTIS 84002733
Qualitative Assessment of the Ignition of Highly Flammable Fuels by Primary Explosives
Elischer, P. P.; De Yong, Leo
Materials Research Labs., Ascot Vale (Australia) (064281000 409014)
Rept no: MRL-R-889, Jun 83, 19p, NTIS Prices: PC A02/MF A01

An assessment of the ignition of fuel/air mixtures and of fabrics soaked with different fuels (ethanol, n-hexane and diethyl ether) by primary explosives has been carried out. (Author)

Fld: 21B, 19A, 91A, 79A
Controlled terms: *Flammability / *Ignition / *Fuels / Test methods / Primers / Igniters / Air / Mixtures / Vapors / Ethanols / Ethers / Ethyl radicals / Hexanes / Fabrics / Saturation
Uncontrolled terms: *Foreign technology / Fuel air mixtures / Diethyl ether / Primary explosives / NTISDODXA / NTISFNAS

AD-P001 771/5 NTIS 83071675

Concrete Bridges Subjected to Impulsive Loading from Fuel-Air Explosives

Hobbs, Brian
Sheffield Univ. (England). Dept. of Civil and Structural Engineering
(023729017 413956)

May 83, 6p, This article is from 'The Interaction of Non-Nuclear Munitions with Structures: Symposium Proceedings Held at U.S. Air Force Academy, Colorado on May 10-13, 1983. Part 2,' AD-A132 116, p139-144, NTIS Prices: PC A02/MF A01

This paper is concerned with an analytical study of the effect of distributed impulsive loading on a range of concrete bridge types. The principal area of interest is collapse behaviour and the establishment of criteria for effective demolition by means of fuel-air explosives. The basis of a simplified analytical approach developed for this work is outlined. Analytical results relating the expected permanent midspan deflection to the total impulse delivered by the explosion are presented. Criteria for effective demolition are discussed and the calculated critical impulse loadings required to cause bridge collapse are shown to range from 13 kNsec/m square to 46 kNsec.m square. These results are compared with those of a previous investigation concerned only with steel bridges

Fld: 19D, 13A, 13B, 79E, 79A, 50B
Controlled terms: *Weapons effects / Explosion effects / Fuel air explosives / Concrete / Bridges / Structural response / Impulse loading / Collapse / Demolition / Steel / Reinforcing materials / Computations / Comparison / Mechanical properties / Strain rate / Sensitivity / Flexural properties / Mathematical prediction / Factor analysis / Conferencing(Communications)
Uncontrolled terms: *Foreign technology / Component reports / NTISDODXA / NTISFNUK

AD-P001 744/2 NTIS 83071648
Simulation of Pressure Waves and Their Effects on Loaded Objects. Part 1. Outlining the Problem, Description of the Simulation Device
Hoffmann, Guenter; Behrens, Karsten
Fraunhofer-Gesellschaft zur Foerderung der Angewandten Forschung e.V., Freiburg im Breisgau (Germany, F.R.). Ernst-Mach-Inst (056913004 413373)
May 83, 5p, This article is from 'The Interaction of Non-Nuclear Munitions with Structures: Symposium Proceedings Held at U.S. Air Force Academy, Colorado on May 10-13, 1983. Part 1,' AD-A132 115, p204-209. See also Part 2, AD-P001 745, NTIS Prices: PC A02/MF A01

Blast wavs generated by detonations of HE or fuel-air-mixtures are characterized by their peak pressure and their overpressure phase duration, i.e. by two parameters. But normally unconfined fuel-air-mixtures will deflagrate generating a pressure time history of a quite different shape. In contrast there is a relatively slow pressure rise up to a peak value followed by a sudden decay into a suction phase the minimum value of which is of the order of the overpressure peak value. The overall duration of this pulse there are more than two parameters necessary for a complete description. Despite the small peak pressure value these waves proved rather dangerous as numerous accidents have shown. Therefore it is desirable to get some insight into the destructive mechanism of these pulses. To be able to do that a special simulation device was developed which will be described. (Author)

FLD: 19D, 19A, 79E, 79A
Controlled terms: *Blast waves / *Explosion effects / *Simulation / *Structural analysis / Simulators / Shock tubes / Detonations / High explosives / Fuel air ratio / Mixtures / Overpressure / Peak values / Pressure / Deflagration
Uncontrolled terms: Component reports / NTISDODXA / NTISFNGE

AD-A125 153/3 NTIS 83029178
Direct Initiation of Detonation in Unconfined Ethylene-Air Mixtures - Influence of Bag Size
Murray, Steven B.; Moen, Ingar O.; Gottlieb, James J.; Lee, John H.; Coffey, Clayton
Defence Research Establishment Suffield, Ralston (Alberta) (007665000 403104)
Rept no: DRES-323, Dec 82, 32p, Presented at the International Symposium on Military Applications of Blast Simulation (7th), Medicine Hat, Alberta, 13-17 Jul 81, NTIS Prices: PC A03/MF A01

The results of a series of field tests performed to determine the critical energy required for initiation of detonation in ethylene-air mixtures are described and discussed, with particular emphasis on the influence of the bag size on the initiation and propagation of detonation. The tests were performed in a plastic bag 10 m long with a cross-sectional area of 1.83 m x 1.83 m using discs of Detasheet explosive as initiator charges at one end of the bag. (Author)

Fld: 19A, 19D, 79A, 79E
Controlled terms: *Fuel air explosives / *Detonations / *Ethylene / *Air / Boundaries / Bags / Sizes(Dimensions) / Field tests / Explosives initiators / Deflagration
Uncontrolled terms: *Foreign technology / Unconfined explosions / NTISDODXA / NTISFNCA

AD-A123 765/0 NTIS 83023479
Design Principles and Practices for Controlling Hazards of Electromagnetic Radiation to Ordnance (HERO Design Guide). Revision 1
Naval Sea Systems Command, Washington, DC (053018000 391345)
Rept no: NAVSEA-OD-30393, 15 Sep 74, 70p, Supersedes report dated 15 Jun 65, NTIS Prices: PC A04/MF A01

Modern communication and radar transmitters can produce high intensity electromagnetic environments that are hazardous to ordnance and to its attending personnel and associated equipment. These environments can cause premature actuation of sensitive electrically initiated explosive elements known as electroexplosive devices (EEDs). They can also damage or trigger solid state circuits, damage or cause erratic readings in test sets, cause possible biological injury to personnel, or produce sparks that can ignite flammable fuel-air mixtures. This Design Guide is intended primarily to help the weapon developer solve the problem of premature actuation of EEDs; however, it should be of some help in solving all of the problems given above. The problem of premature actuation of EEDs is known as Hazards of Electromagnetic Radiation to Ordnance (HERO). (Author)

Fld: 19A, 20N, 79A
Controlled terms: *Electromagnetic radiation / *Hazards / *Explosives initiators / *Ordnance / Sparks / Radar transmitters / Test sets / Trigger circuits / Electromagnetic environments / Flammability / Wounds and injuries / Mixtures / Fuels / Air /

AD-A122 700/3 NTIS 83018231
A Brief Description of the DRES Fuel-Air Explosives Testing Facility and Current Research Program
Funk, J. W.; Murray, S. B.; Ward, S.; Moen, I. O.
Defence Research Establishment Suffield, Ralston (Alberta) (007365000 403101)
Rept no: DRES-MEMO-1053, Sep 82, 26p, Presented at the International Specialist Meeting on Fuel-Air Explosions, McGill University, Montreal, 4-6 Nov 81, NTIS Prices: PC A03/MF A01

The key features of the fuel-air explosives (FAE) field testing facility at the Defence Research Establishment Suffield (DRES) are described. The current test program at DRES is focused on critical conditions for initiation and transmission of detonation in ethylene-air mixtures. This program includes an investigation of the influence of confinement on the propagation of detonation. Selected results from these investigations are discussed and typical photographic and smoked-foil records obtained during the current test program are included. (Author)

Fld: 19A, 19D, 79A, 79E
Controlled terms: *Test facilities / *Fuel air explosives / Detonations / Transmittance / Ethylenes / Smoke / Clouds / Air mass analysis / Gas flow / Field tests / Experimental data / Research management
Uncontrolled terms: *Foreign technology / NTISDODXA / NTISFNCA

AD-A122 296/7 NTIS 83013292
Detonation Characteristics of Some Dusts and Liquid-Dust Suspensions
Kauffman, C. W.; Nicholls, J. A.; Sichel, M.; Lee, P.; Wood, K.
Michigan Univ., Ann Arbor. Dept. of Aerospace Engineering.*Air Force Office of Scientific Research, Bolling AFB, DC (002797148 402605)
Annual rept. 1 Mar 81-1 May 82, Rept no: UM-016968-3, Jul 82, 21p, Grant: AFOSR-79-0093, Project: 2308, Task: A2, Monitor: AFOSR-TR-82-1026, NTIS Prices: PC A02/MF A01

This report presents progress on a study of the detonation properties of high explosive dusts when dispersed in air and suspended in liquids. The experimental facility is a modified form of a shock tube wherein the dust is blown through the tube and then a strong shock wave is transmitted into the heterogeneous mixture. The main objective of this research is to determine the detonation characteristics of dusts when dispersed in air under unconfined conditions. Important factors which bear on this problem, and hence which could be investigated, include the properties of the dust, the concentration of the dust, the size of the dust particles, the effects of excess oxygen, the energy of the initiating source, and the structure of the reaction zone. For a range of conditions, then, it is desirable to determine the pressure history within and behind the reaction zone, the wave velocity, the ignition time delay of the particles behind the leading shock wave, and to obtain high speed streak and framing photographs of the wave and reaction zone. The experimental results would be utilized in connection with an analytical treatment to develop a model for the initiation of such detonations. An interesting ramification of this research is the three-phase detonation. That is, the detonability aspects of dust particles entrained in liquid fuel droplets

FLD: 19D, 79E
Controlled terms: *Detonations / *Explosions / *Dust / Ignition lag / Explosives initiators / Liquids / Mixtures / Drops / Fuel air ratio / Energy / Particles / Shock waves / Shock tubes / High explosives / Time intervals
Uncontrolled terms: Dust suspensions / NTISDODXA / NTISDODAF

AD-A119 197/2 NTIS 83070337
Energy Release from Condensed Phase Materials and Heterogeneous Reactive Flow Modeling
Kailasanath, Kazhikathra; Hyman, Ellis
Science Applications, Inc., McLean, VA.*Shared Bibliographic Input (050165000 108401)
Final rept. 13 Jun 81-17 Jun 82, Rept no: SAI-83-831-WA, Jul 82, 67p, Contract: N00014-81-C-2419, Monitor: SBI-AD-E001-333, NTIS Prices: PC A04/MF A01

This report describes the results from investigations on (1) the burning velocity of hydrogen in air, (2) the direct initiation of detonations in hydrogen air mixtures and (3) the flow in and about fuel droplets

Fld: 19A, 79E
Controlled terms: *Compressible flow / *Hydrogen / *Detonations / *Energy transfer / Air / Flames / Shock tubes / Incompressible flow / Computerized simulation / Fuel air explosives / Mixtures / Drops / Models
Uncontrolled terms: Reactive flow / Low models / NTISDODXA

AD-A116 681/3 NTIS 82255596
Adiabatic Computation of Internal Blast from Aluminum-Cased Charges in Air
Reinhardt, Richard A.; McDonald, Andrea K.
Naval Postgraduate School, Monterey, CA.*Naval Weapons Center, China Lake, CA.*Shared Bibliographic Input (019893000 251450)
Technical publication 1980-1981, Rept no: NWC-TP-6237, Jan 82, 34p, Project: F32300, Task: WF32300000, Monitor: NWC-TP-6237, SBI-AD-E450-029, NTIS Prices: PC A03/MF A01

Calculations have been carried out, using the HP9845A desktop computer, for the maximum overpressures developed by combustion of fuels plus aluminum in confined air volumes. In all, eight fuels were chosen, both conventional and explosive. The mass of fuel to that of metal was varied from 0.1 to 10.0 and the total concentration of fuel plus metal ranged from 0.1 to 10.0 kilograms per cubic meter of incident air. The computations include evaluation of the adiabatic temperatures and of the product compositions, the latter involving the chemical equilibria amongst 23 gaseous and up to five condensed-phase substances

Fld: 19A, 19D, 79A, 79E
Controlled terms: *Adiabatic conditions / *Calculators / *Aluminized explosives / *Fuel air explosives / Overpressure / Air
Uncontrolled terms: NTISDODXA / NTISDODN

AD-A109 057/0 NTIS 82013763
Initiation, Combustion and Transition to Detonation in Homogeneous and Heterogeneous Reactive Mixtures: A Summary
Strehlow, Roger A.; Barthel, Harold O.; Krier, Herman
Illinois Univ. at Urbana-Champaign. Dept. of Aeronautical and Astronautical Engineering.*Air Force Office of Scientific Research, Bolling AFB, DC (034597070 176005)
Final rept. 1 Jun 80-31 May 81, Sep 81, 76p, Grant: AFOSR-77-3336, Project: 2303, Task: A1, Monitor: AFOSR-TR-81-0840, NTIS Prices: PC A05/MF A01

Certain aspects of ignition source effects in reactive fuel-air mixtures are discussed. These aspects include effects of chemical sensitizers, flame acceleration, flame area, and ignition point location. The other area involves the hydrodynamic modeling of ignition and flamespreading in granular energetic solids to predict the potential for deflagration-to-detonation transition (DDT). Key results in the first area are that chemically sensitized clouds can lead to detonation, that flame acceleration or a large increase in the time rate of increase of the flame area are needed for transition from deflagration to detonation and that it is very difficult to generate damaging overpressure from edge-ignited combustion even for very high subsonic burning velocities. The research dealing with analysis of DDT in porous high energy solid propellant has shown (for the first time) actual steady-state detonation solutions, following the unsteady flow, for materials with sufficient porosity and critical burning rate properties. Limits of the run-up length to detonation are predicted as a function of propellant chemical energy, burning rate, bed porosity, and granulation (size). The detonation states conform to realistic measured conditions for porous HMX and RDX propellants

Fld: 21B, 19D, 81A, 79E
Controlled terms: *Ignition / *Combustion / *Fuel air explosives / *Mixtures / Flames / Detonations / Deflagration / Transitions / Shock waves / Blast waves / Solid propellants / RDX / Reaction kinetics / Hydrodynamics / Models / Porosity / Heterogeneity / Damage / Overpressure
Uncontrolled terms: NTISDODXA / NTISDODAF

AD-A108 977/0 NTIS 82019684
1981 AFOSR Contractors Meeting on Air Breathing Combustion Dynamics and Explosion Research, 16-20 November 1981, Clearwater Beach, Florida
Wolfson, B. T.; Gerstein, M.; Choudhury, Roy
University of Southern California, Los Angeles, Dept. of Mechanical Engineering.*Air Force Office of Scientific Research, Bolling AFB, DC (013356007 402431)
Interim rept, Sep 81, 193p, Grant: AFOSR-77-3354, Project: 2308, Task: A2, Monitor: AFOSR-TR-81-0344, NTIS Prices: PC A09/MF A01

The report consists of a collection of expanded abstracts of the numerous research progress reports given by AFOSR supported contractors on the Air Force basic research program on Energy Conversion Related to Air-Breathing Propulsion and Explosions and of invited papers from other governmental agencies and contractors. These papers presented over a five-day period composed the 1981 contractors meeting on Air-Breathing Combustion Dynamics and Explosion Research. The principal investigators and their organizational association are also identified. (Author)

Fld: 21B, 21E, 21A, 81D, 81A
Controlled terms: *Combustion / *Dynamics / *Air breathing engines(Unconventional) / *Explosions / Symposia / Contracts / Personnel / Abstracts / Energy conservation / Gas turbines / Ramjet engines / Models / Fuel air explosives / Ignition / Burning rate / Combustion stability / Particles / Fire extinguishing agents / Homogeneity
Uncontrolled terms: Combustion instability / Particle dynamics / Heterogeneous combustion / NTISDODXA / NTISDODAF

AD-A108 772/0 NTIS 82000031
Countermine Warfare Analysis
Honeywell, Inc., Hopkins, MN. Mission Analysis Group (012263006 412523)
Final rept, Rept no: 47812, Jun 81, 100p, Contract: DAAK70-79-C-0040, NTIS Prices: PC A05/MF A01

The specific objectives of the Countermine Warfare Analysis were: To identify the principles, precepts, and trends in mining and countermining warfare that were established in World War II combat and assess their relevance to contemporary warfare, and To determine the potential impact of countermining operations on the modern battlefield

Fld: 15G, 15C, 74G, 74I
Controlled terms: *Countermining / *Land mine warfare / Antivehicle weapons / Mine detection / Tactical communications / Mine neutralization / Combat vehicles / Mine clearance / Rollers / Magnetic signatures / Fuel air explosives / Surface launched / USSR / Tactical analysis
Uncontrolled terms: VEMASID(Vehicle Magnetic Signature Duplicators) / Mine clearance vehicles / Scatterable mines / SLUFAE(Surface

AD-A096 415/3 NTIS 81031626
Chemical Initiation of FAE Clouds
Von Elbe, G.; McHale, E. T.
Atlantic Research Corp., Alexandria, VA. Combustion and Physical Science Dept.*Air Force Office of Scientific Research, Bolling AFB, DC (003297032 400016)
Final rept. 1 May 77-30 Sep 80, Nov 80, 27p, Contract: F49620-77-C-0037, Project: 2308, Task: A2, Monitor: AFOSR-TR-81-0253, NTIS Prices: PC A03/MF A01

Laboratory experiments with liquid fuel and ClF3 (CTF) or BrF3 (BTF) have suggested that an effective FAE blast may be obtained by very rapid fuel/agent dispersion and agent-induced combustion. Initial small-scale field tests using pellets of high-explosive for fuel and agent dispersion have yielded significant FAE blast when performed in open air, no blast when performed in an atmosphere of nitrogen, and a very strong blast when performed in an atmosphere of oxygen. A jet-structured FAE cloud of dispersed fuel and CTF has been demonstrated in which the combustion air is entrapped between the jets and entrained and burned as the jets explode. The jets are generated by the combined effects of taylor instability and indentations in the dispersing explosive charge. The mass flow that is induced by the cloud explosion generates a coherent shock wave. In the present small-scale tests, the flow is strongly divergent and the shock Mach number is only of the order of 3. In a large-scale cylindrical FAE configuration, the shock wave would not be attenuated by flow divergence and the shock Mach number would be expected to be of the order of 4 to 5. In that case, the shock wave is expected to become a detonation wave much like the detonation wave in an FAE cloud with second-event initiation. (Author)

FLD: 19A, 19D, 79A, 79E
Controlled terms: *Fuel air explosives / *Fuels / *Oxidizers / *High explosives / *Blast / Dispersions / Clouds / Jet flow / Explosive charges / Shock waves / Detonation waves / Chlorine compounds / Bromides / Fluorides
Uncontrolled terms: Chlorine trifluoride / Bromine trifluoride / NTISDODXA / NTISDODAF

AD-3017 905/1 NTIS 81003193
DICE-FAE Analysis of Fuel Dispersal and Detonation from Fuel-Air-Explosive Device
Rosenblatt, Martin; Eggum, Gordon E.; Kreyenhagen, Kenneth N.
California Research and Technology, Inc., Woodland Hills (0586200 391223)
Final rept. 25 Oct 75-25 Feb 76, Rept no: CRT-5080-1, Mar 76 143p, Contract: F08635-76-C-0082, Project: 2513, Task: 07 Monitor: AFATL-TR-76-33, Distribution limitation now removed, NTI Prices: PC A07/MF A01

Using the DICE-FAE code, a numerical solution was generated of bot the dispersal and detonation phases for a BLU-73 liqui Fuel-Air-Explosive device. DICE-FAE is a two-dimensional, implicit Eulerian, finite difference code which treats fuel-air mixtures, fue droplet break-up, fuel phase changes, and fuel-air detonatic dynamics. The fuel droplets flow through the air and interact with th air through drag and heat exchange mechanisms. The cloud disperse analysis started with initial conditions representing the fuel mas and burster products just after canister break-up. The FAE detonatic analysis commenced with the calculated dispersed cloud fuel-ai characteristics and with second event initiation by centrally-located explosive charge. Detailed comparisons from th DICE-FAE results and experimental data have not been completed, bu the final calculated cloud dimensions and peak detonation pressure appear reasonable. The computational results also provide a detaile prediction in terms of space and time of the fuel concentration during the dispersal phase and of the pressures and temperature during the detonation phase. (Author)

FIG: 19A, 19D, 93, 90I, 79A, 79E, 79C
Controlled terms: *Fuel air explosives / *Dispersing / *Detonation / *Machine coding / Mathematical models / Finite difference theory Computerized simulation / Mixtures / Density / Drops / Explosiv charges
Uncontrolled terms: Dice-Fae code / Blu-73 bombs / NTISDODXD

AD-B017 905/1 NTIS 81005300
DICE-FAE Analysis of Fuel Dispersal and Detonation from a Fuel-Air-Explosive Device
Rosenblatt, Martin; Eggum, Gordon E.; Kreyenhagen, Kenneth N.
California Research and Technology, Inc., Woodland Hills (053620000 391223)
Final rept. 25 Oct 75-25 Feb 76, Rept no: CRT-5090-1, Mar 76, 143p, Contract: F08635-76-C-0082, Project: 2513, Task: 07, Monitor: AFATL-TR-76-33, Distribution limitation now removed, NTIS Prices: PC A07/MF A01

Using the DICE-FAE code, a numerical solution was generated of both the dispersal and detonation phases for a BLU-73 liquid Fuel-Air-Explosive device. DICE-FAE is a two-dimensional, implicit, Eulerian, finite difference code which treats fuel-air mixtures, fuel droplet break-up, fuel phase changes, and fuel-air detonation dynamics. The fuel droplets flow through the air and interact with the air through drag and heat exchange mechanisms. The cloud dispersal analysis started with initial conditions representing the fuel mass and burster products just after canister break-up. The FAE detonation analysis commenced with the calculated dispersed cloud fuel-air characteristics and with second event initiation by a centrally-located explosive charge. Detailed comparisons from the DICE-FAE results and experimental data have not been completed, but the final calculated cloud dimensions and peak detonation pressures appear reasonable. The computational results also provide a detailed prediction in terms of space and time of the fuel concentrations during the dispersal phase and of the pressures and temperatures during the detonation phase. (Author)

Fld: 19A, 19D, 9B, 90I, 79A, 79E, 79C
Controlled terms: *Fuel air explosives / *Dispersing / *Detonations / *Machine coding / Mathematical models / Finite difference theory / Computerized simulation / Mixtures / Density / Drops / Explosive charges
Uncontrolled terms: Dice-Fae code / Blu-73 bombs / NTISDODXD

AD-A036 615/2 NTIS 30049099
On the Concept of the Critical Size od a Detonation Kernel
Lee, John H.; Ramamurthi, K.
McGill Univ Montreal (Quebec) Dept of Mechanical Engineering*Air Force Office of Scientific Research, Bolling AFB, DC (223165)
9 Sep 75, 12p, Grant: AFOSR-72-2387, Project: 9711, Task: 02, Monitor: AFOSR-TR-77-0559, Pub. in Combustion and Flame, v27 p331-340 1976, NTIS Prices: PC A02/MF A01

No abstract available

Fld: 19D, 19A, 79E, 79A
Controlled terms: *Detonations / *Fuel air explosives / *Sizes(Dimensions) / Gases / Limitations / Reprints
Uncontrolled terms: Kernels(Detonators) / NTISDODXP / NTISFNC?

AD-A036 219/3 NTIS 80046756
Feasibility Investigation of a Permanent Fuel-Air Explosive Blast Simulator
Sedgwick, R. T.; Kratz, H. B.; Herrmann, R. G.
Systems Science and Software La Jolla CA*Defense Nuclear Agency, Washington, DC*Shared Bibliographic Input Experiment (388507)
Topical rept. 9 May 77-9 Aug 78, Rept no: SSS-R-78-3737, 9 Aug 78, 116p, Contract: DNA001-77-C-0251, Project: Y99QAXS, Task: D070, Monitor: AD-E300-312, NTIS Prices: PC A07/MF A01

Initial results from an investigation to determine the feasibility of using fuel-air-explosives (FAE) to simulate the airblast from a 1 KT nuclear blast are reported. A small scale blast facility was developed and tested. Up to 22.7 kg (50 lbs) of fuel such as propylene oxide can be disseminated through a hemispherical nozzle head containing 600 nozzles to form 9.14 m (30 ft) diameter hemispherical clouds which are subsequently detonated. The measured pressure history and impulse from several experiments were scaled and compared with 1 KT nuclear blast wave data. These initial results indicate that FAE can be used to simulate nuclear blast waves and that continued effort to develop the technology required to design a permanent, reuseable 1 KT FAE nuclear blast wave facility is therefore warranted. (Author)

FlD: 19D, 18C, 79E, 77D
Controlled terms: *Nuclear explosion simulation / *Fuel air explosives / *Airburst / *Blast / Blast waves / Propenes / Oxides / Nozzles / Test facilities / Feasibility studies
Uncontrolled terms: NTISDODXA / NTISDODSD

AD-A084 743/1 NTIS 80040922
Cylindrical Heterogeneous Detonation Waves
Nicholls, J. A.; Sichel, M.
Michigan Univ Ann Arbor Gas Dynamics Labs*Army Research Office, Research Triangle Park, NC (401459)
Final rept. 20 Feb 77-29 Feb 80, Rept no: UM-015242-F, May 80, 14p, Grant: DAAG29-77-G-0104, DAAG29-78-G-0116, Monitor: ARO-14417.4-E, ARO-15925.1-A-E, NTIS Prices: PC A02/MF A01

Heterogeneous detonation refers to the fact that the fuel is in one physical state and the oxidizer in a different one. In these studies the fuel was in the form of liquid drops and the oxidizer was gaseous. This research program treated the blast wave initiation of heterogeneous detonation, the propagation of heterogeneous detonation through uniform and non-uniform clouds, and the influence of different fuels and/or different properties. The study involved theoretical as well as experimental work. An existent sectored shock tube, designed to model a cylindrical heterogeneous fuel-air cloud, was significantly enlarged and improved. Cylindrical blast waves of controllable strength were driven into the cloud by firing a condensed explosive at the apex of the sector. A number of fuels were tested; i.e. kerosene, decane, heptane, and kerosene mixed with normal propyl nitrate. A number of mixture ratios were investigated. The initiator energy levels required to establish detonation were noted for some cases. Heptane represented a case of high vapor pressure whereas decane, very similar in other respects, represented a low vapor pressure case. Significant differences were noted

Fld: 19D, 19A, 21B, 79E, 79A
Controlled terms: *Detonation waves / *Blast waves / Fuel air explosives / Heterogeneity / Wave propagation / Drops / Gases / Combustion / Vapor pressure / Ignition / Delay / Shock tubes / Model tests / Decanes / Kerosene / Heptanes / Propyl radicals / Nitrates
Uncontrolled terms: Cylindrical blast waves / Propyl nitrate / NTISDODXA / NTISDODA

AD-A033 294/9 NTIS 80031855
Fuel-Air Explosions in a Fog Oil Smoke Environment
Sullivan, John D.; Reitz, Richard G.
Army Armament Research and Development Command Aberdeen Proving Ground MD Ballistics Research Lab*Shared Bibliographic Input Experiment (393171)
Final rept, Rept no: ARBRL-MR-02935, Jan 80, 33p, Project: 1L162618AH80, Monitor: AD-E430-393, NTIS Prices: PC A03/MF A01

A fuel-air explosion was investigated as a means of neutralizing a smoke screen of fog oil. On three runs a spray of propylene oxide was detonated inside a tactical fog cloud. The FAE did not ignite the fog oil cloud nor was any clearance evinced as judged by visual observation and camera and television recordings. Transmissometers with lines-of-sight through the clouds operated in the visible and three infrared bands. Immediately after detonation, the transmittance was reduced in all four spectra bands. The reduction in transmittance was probably a result of dust lofted by the FAE. It was concluded that tactical fog oil clouds are very probably too lean to ignite. There was no difficulty in detonating a fuel-air cloud in the covering fog oil cloud

Fld: 19A, 19D, 79A, 79E
Controlled terms: *Fuel air explosives / *Smoke screens / *Smoke / *Explosions / *Detonations / Smoke munitions / Fog dispersal / Fog / Infrared spectra / Transmissometers / Transmittance / Dust / Smoke generators / Tables(Data) / Test methods / Fuel sprays / Fuel oil / Band spectra / Ignition / Neutralization / Visible spectra / Clouds / Environments / Propyl radicals / Polypropylene / Ethylene oxide / Dust explosions / Tactical warfare
Uncontrolled terms: Fog oil / Propylene oxide / Visual observation / Fuel air clouds / NTISDODXA

AD-A082 610/7 NTIS 80028611
Chemical Initiation of FAE Clouds
von Elbe, G.; McHale, E. T.
Atlantic Research Corp Alexandria VA Combustion and Physical Science Dept*Air Force Office of Scientific Research, Bolling AFB, DC (400016)
Annual interim rept. Sep 78-Sep 79, Nov 79, 37p, Contract: F49620-77-C-0037, Project: 2308, Task: A2, Monitor: AFOSR-TR-80-0113, NTIS Prices: PC A03/MF A01

Laboratory experiments with liquid fuel and ClF3 (CTF) or BrF3 (BTF) have suggested that an effective FAE blast may be obtained by very rapid fuel/agent dispersion and agent-induced combustion. In the current work, initial small-scale field tests using small pellets of high-explosive for fuel and agent dispersion have yielded significant FAE blasts when performed in open air, no blast when performed in an atmosphere of nitrogen, and a very strong blast when performed in an atmosphere of oxygen. The results show that an agent such as CTF meets the requirements of inducing very rapid combustion, and that the strength of the FAE blast is thus principally governed by the size and configuration of the central dispersing charge. Further small-scale tests are scheduled in which the central charge is substantially enlarged and shaped for injecting high velocity jets of fuel/agent dispersion into the surrounding atmosphere. (Author)

Fld: 21D, 19D, 7D, 97K, 79E, 99F
Controlled terms: *Fuel air explosives / *Ignition / Reaction kinetics / Autoignition / Test methods / Field tests / Pellets / Nitrogen / Blast / Oxygen / Liquids / High velocity / Dispersions / Laboratory tests / Explosive actuators / Explosive charges
Uncontrolled terms: NTISDODXA / NTISDODAF

AD-A073 176/5 NTIS 80011042
The Blast Wave Generated by Spherical Flames
Strehlow, R. A.; Luckritz, R. T.; Adamczyk, A. A.; Shimpi, S. A.
Illinois Univ At Urbana-Champaign Dept of Aeronautical and Astronautical Engineering*Air Force Office of Scientific Research, Bolling AFB, DC (176075)
20 Jul 77, 16p, Grant: AFOSR-77-3336, AFOSR-77-2524, Project: 2308, Task: A2, Monitor: AFOSR-TR-79-1172, Pub. in Combustion and Flame, v35 p297-300 1979, NTIS Prices: PC A02/MF A01

No abstract available

Fld: 19D, 79E
Controlled terms: *Blast waves / *Flame propagation / Flames / Spheres / Interactions / Explosions / Fuel air explosives / Reprints
Uncontrolled terms: *Spherical blast wave theory / NTISDODXR / NTISDODAF

3 AD-A081 367/2 NTIS 80036778

Fundamental Mechanisms of Unconfined Detonation of Fuel-Ai Explosions

Knystautas, R.; Lee, J. H.; Moen, I. O.
McGill Univ Montreal (Quebec) Dept of Mechanical Engineering*Air Force Office of Scientific Research, Bolling AFB, DC (223165)

Interim rept. 1 Jan-31 Dec 79, Feb 80, 100p, Grant: AFOSR-77-3230
, Project: 2308, Task: A2, Monitor: AFOSR-TR-80-0323
Availability: Microfiche copies only, NTIS Prices: MF A01

Research during the past year has led to some significant results which have profound implications in the area of vapor cloud explosion in general, and in the area of 'shockless' initiation of detonation in particular. In brief we have; (i) demonstrated experimentally that initiation of detonation can be achieved by injecting a chemical catalyst into a fuel-air mixture, (ii) demonstrated experimentally that direct initiation can be achieved by seeding an explosive mixture with free radicals of the appropriate concentration and spatial distribution, (iii) demonstrated experimentally that direct initiation can be achieved via turbulent mixing between an explosive mixture and its combustion products, (iv) demonstrated experimentally that unconfined turbulent flame speeds exceeding 400 m/s can readily be achieved in a mixture as inert as methane air, (v) clarified through experiments the role of confinement on the propagation of detonations near the detonability limits, and (vi) assessed the far field destructive potential of FAE weapons by calculating numerically the effective blast energy of non-ideal blast waves generated by vapor cloud explosions. (Author)

Fld: 19D, 19A, 21B, 79E, 79A, 81A
Controlled terms: *Detonations / *Fuel air explosives / *Flame propagation / Combustion products / Turbulent diffusion / Mixing / Reaction kinetics / Catalysts / Volume / Vapors / Free radicals / Injection / Detonation waves / Confinement(General) / High acceleration / Blast waves / Far field / Fluorine / Propane / Methane / Air
Uncontrolled terms: *Foreign Technology / Vapor cloud explosions / Detonation initiation / Unconfined detonation / NTISDODXA / NTISFNCA / NTISDODAF

AD-D006 433/6 NTIS 80007336
Method for Fuel Air Explosive
Falterman, Charles W.; Bowen, James A.; Josephson, Larry H.
Department of the Navy Washington DC (001840000)
Patent, Rept no: PAT-APPL-339 662, PATENT-4 157 928, Filed 1 Mar 73, patented 12 Jun 79, 4p, Monitor: 18, Supersedes PAT-APPL-339 662-73, Availability: This Government-owned invention available for U.S. licensing and, possibly, for foreign licensing. Copy of patent available Commissioner of Patents, Washington, DC 20231 $0.50, NTIS Prices: Not available NTIS

This report discusses mixtures of ethylene oxide and propylene oxide that are disclosed as being useful as fuels for fuel air explosive weapons

Fld: 19A, 99B, 79A
Controlled terms: *Patents / *Fuel air explosives / *Weapons / *Ethylene oxide / *Propylene oxide / Mixtures / Containers / Boosters(Explosives) / Tetryl / Bomblets / Detonators / Clouds / Polymerization / Vapor pressure / Low temperature
Uncontrolled terms: PAT-CL-149-109-2 / Propylene oxide / NTISGPN

AD-A073 765/0SL NTIS 79055768
Proceedings of the Nuclear Blast and Shock Simulation Symposium, 28-30 November 1978, Volume I
General Electric Co Santa Barbara CA TEMPO*Defense Nuclear Agency, Washington, DC*Shared Bibliographic Input Experiment (346420)
Dec 78, 455p, Contract: DNA001-79-C-0081, Project: P99QAXD, Task: C008, Monitor: DNA-4797P-1, AD-E300-569, See also Volume 2, AD-A073 766, NTIS Prices: PC A20/MF A01

This report contains the papers presented at the Proceedings of the Nuclear Blast and Shock Simulation Symposium held 28-30 November 1978 at the Naval Ocean Systems Center, San Diego, California, under the sponsorship of the Shock Physics Strategic Structures Division (SPSS) of the Defense Nuclear Agency. The Symposium provided a forum for the exchange of information on technical approaches and recent accomplishments in the development of nuclear blast and shock simulators. Volume I contains papers on the following topics: Site Selection and Environmental Considerations; Airblast/Thermal Effects Simulation; and Underwater Shock Simulation

Fld: 19D, 18C, 79E, 77D
Controlled terms: *Blast / *Shock / *Nuclear explosion simulation / Symposia / Blast waves / High explosives / Shock waves / Site selection / Test facilities / Simulators / Fuel air explosives / Pressure measurement / Thermal radiation / Solar furnaces / Underwater explosions / Simulation / Weapons effects / Underwater
Uncontrolled terms: Airburst / *Meetings / NTISDODXA / NTISDODSD

AD-A073 058/9SL NTIS 79053352
Initiation, Combustion and Transition to Detonation in Homogeneous and Heterogeneous Reactive Mixtures
Strehlow, Roger A.; Barthel, Harold O.; Krier, Herman
Illinois Univ at Urbana-Champaign Dept of Aeronautical and Astronautical Engineering*Air Force Office of Scientific Research, Bolling AFB, DC (176005)
Interim rept. 1 Jun 78-31 May 79, Jul 79, 53p, Grant: AFOSR-77-3336, Project: 2308, Task: A1, Monitor: AFOSR-TR-79-0934, NTIS Prices: PC A04/MF A01

The research deals with the broad topics of initiation, combustion and transition to detonation in homogeneous and heterogenous reactive mixtures. One specific area deals with analytical and experimental work directed to direct initation of detonation by a nonideal blast wave in chemically sensitized reactive fuel-air clouds. The other specific topic involves the hydrodynamic modeling of ignition and flamespreading in granular energetic solids to predict the potential for deflagration-to-detonation (DDT)

FLD: 21B, 19D, 81A, 79E
Controlled terms: *Ignition / *Combustion / *Flame propagation / *Detonations / Deflagration / Transitions / Shock waves / Blast waves / Fuel air explosives / Solid propellants / Propellant grains / Mathematical models
Uncontrolled terms: NTISDODXA / NTISDODAF

AD-A072 623/2SL NTIS 79051008
An Investigation of the Ignition Delay Times for Propyler Oxide-Oxygen-Nitrogen Mixtures
Meister, Earl Edward III
Illinois Univ at Urbana-Champaign Dept of Aeronautical an Astronautical Engineering*Air Force Office of Scientific Research Bolling AFB, DC (176005)
Interim technical rept, Rept no: AAE-78-4, UILU-ENG-79-0504, Oc 78, 37p, Grant: AFOSR-77-3336, Project: 2308, Task: A2, Monitor AFOSR-TR-79-1423, NTIS Prices: PC A03/MF A01

A reflected shock tube technique has been used to measure th ignition delay time for propylene oxide-oxygen-nitrogen mixtures i the temperature range of 900 to 1250 deg K. Ignition delay times wer measured by using both streak schlieren and pressure gauges mounted c the back wall of the shock tube. A regression analysis indicated tha the delay time multiplied by the propylene oxide concentration to th .8 power and the oxygen concentration to the -1.2 power yielded a bes fit when plotted as a logarithm against the reciprocal temperature This regression analysis also indicated that the nitroge concentration had no effect on the ignition delay time. The apparen activation energy for the reaction was found to be approximately 1 kcal joule/mole

FLD: 19A, 21B, 14B, 79A, 81A, 99A
Controlled terms: *Fuel air explosives / *Ignition lag / *Fuel ai ratio / *Shock tubes / Delay / Mixtures / Argon / Oxygen / Epox compounds / Nitrogen / Physical properties / Safety / Accidents Activation energy / Ignition / Detonations / Experimental data Temperature / Heat of reaction / Data processing / Test equipment Computer programs
Uncontrolled terms: Ignition delay / Propylene oxides / NTISDODXA NTISDODAF

AD-A068 712/5SL NTIS 79040747
Report on the AFOSR Workshop on FAE III
Moen, Ingar O.
McGill Univ Montreal (Quebec) Dept of Mechanical Engineering*Air Force Office of Scientific Research, Bolling AFB, DC (223165)
Interim rept, Jan 79, 70p, Grant: AFOSR-77-3207, Project: 2308, Task: A2, Monitor: AFOSR-TR-79-0594, NTIS Prices: PC A04/MF A01

This report is based on the Workshop on FAE III held at Fort Walton Beach, Florida, January 25, 1979. The current status of the FAE III single event concept is reviewed. Mechanisms of volumetric initiation without shock waves produced by an external source are discussed, with particular emphasis on the SWACER mechanism of detonation initiation. The use of a chemical sensitizer (initiator) to trigger the fuel-air ignition and subsequent onset of detonation in a fuel-air cloud are discussed. Proposed approaches to achieving an FAE III device are discussed, and directions for future research to obtain proof of the FAE III single event concept are indicated. (Author)

FLD: 19A, 79A
Controlled terms: *Fuel air explosives / Workshops / Explosives initiators / Detonations / Shock waves / Sensitizing / Ignition / Volumetric analysis / Fuel air ratio / Mixtures / Reaction kinetics
Uncontrolled terms: *Meetings / NTISDODXA / NTISDODAF

AD-A067 334/3SL NTIS 79033731
Variable Energy Blast Waves and Two Phase Detonations
Dabora, E. K.
Connecticut Univ Storrs Dept of Mechanical Engineering*Army Research Office, Research Triangle Park, NC (410454)
Final rept. 1 Jan 73-30 Sep 78, Rept no: UCCNN-0507-121-F, Feb 79, 52p, Grant: DA-ARO-D-31-124-73-G100, DAAG29-76-G-0142, Monitor: ARO-11052.5-E, ARO-13193.3-E, Sponsored in part by Grant DAAG29-77-G-0112, NTIS Prices: PC A04/MF A01

The results of the research work performed to determine the role of blastwaves and mass addition within the reaction zone of spray detonations are summarized. Since most of the findings have been published in the literature, abstracts of the relevent publications have been included. One of the publications describes a model for spray detonations in which the relevant parameters are found to be the ignition delay and the energy temporal variation within the reaction zone. The model can predict the minimum energy for direct initiation when these parameters are known. Recent experiments on laser ignition of fuel drops to simulate the mass addition aspect within the reaction zone are reported in detail. These experiments indicate the mass addition effects are small when compared to the blast wave effects. However, they reveal that, under some conditions, explosive combustion can take place. The experiments appear to be the first of their kind and open up new avenues for research on liquid propellants, fuel-air explosions and detonation transfer. (Author)

FLD: 19D, 19A, 79E, 79A
Controlled terms: *Detonation waves / *Blast waves / Fuel sprays / Liquid propellants / Fuel air explosives / Energy transfer / Two phase flow / Drops / Laser beams / Ignition / Time dependence / Combustion
Uncontrolled terms: Spray detonations / NTISDODXA / NTISDODA

AD-A061 799/9SL NTIS 79024371
AFOSR Contractors Meeting (1978) on Unconfined Fuel-Air Explosions (FAE) and other Combustion/Explosion Related Research Held at Fort Walton Beach, Florida, on January 22-24, 1979
Atlantic Research Corp., Alexandria, VA.*Air Force Office of Scientific Research, Bolling AFB, DC (043550)
Interim rept, Jan 79, 64p, Contract: F49620-79-C-0097, Project: 2308, Task: A2, Monitor: AFOSR-TR-79-1126, NTIS Prices: PC A04/MF A01

The report consists of a collection of abstracts of the numerous research progress reports given by AFOSR contractors and of invited papers from other governmental agencies and CONUS and European contractors. These papers presented over a three day period composed the annual contractors meeting on combustion dynamics associated with fuel-air explosions and other explosion related phenomena. The principal investigators and their organizational association are also identified. (Author)

Fld: 19A, 19D, 79A, 79E
Controlled terms: *Fuel air explosives / Reports / Abstracts / Combustion / Ignition / Deflagration / Flameout / Detonations / Particle size / Homogeneity / Heterogeneity
Uncontrolled terms: *Meetings / NTISDODXA / NTISDODAF

AD-A064 676/9SL NTIS 79024443
Failure and Post Buckling Behavior of Thin Cylindrical Shells
Strickland, William S.; Ross, Claudius A.
Air Force Armament Lab., Eglin AFB, FL (403936)
Final rept. Nov 75-Jan 77, Rept no: AFATL-TR-77-52, Apr 77, 46p, Project: 2549, Task: 02, Monitor: 18, NTIS Prices: PC A03/MF A01

This report presents experimental data on the response of thin cylindrical shells to blast loads. Blast loading over cylindrical surfaces, failure, and buckling modes are examined in an effort to establish a base for post buckling and failure modelings. (Author)

Fld: 19D, 19A, 79E, 79A
Controlled terms: *Shells(Structural forms) / *Impulse loading / *Buckling / *Fuel air explosives / Cylindrical bodies / High explosives / Blast / Failure / Thin walls / Plastic deformation / Experimental data / Mathematical models
Uncontrolled terms: *Cylindrical shells / NTISDODXA

AD-D005 475/9SL NTIS 79012640
Explosive Closure Valve
Lopez, Alvaro G.
Department of the Navy Washington DC (110050)
Patent, Rept no: PAT-APPL-706 869, PATENT-4 039 900, Filed 19 Jul 76, patented 2 Aug 77, 3p, Monitor: 18, Supersedes PAT-APPL-706 869-76, AD-D003 156, Availability: This Government-owned invention available for U.S. licensing and, possibly, for foreign licensing. Copy of patent available Commissioner of Patents, Washington, DC 20231 $0.50, NTIS Prices: Not available NTIS

An explosive closure valve that provides a fast acting seal at an explosive interface is described. The valve is attached to an interface wall. It operates such that a piston in the valve moves at right angles to the path of a detonating explosive element thereby, positively blocking the hole left by the expended explosive element

Fld: 13K, 19D, 94, 79E, 90A
Controlled terms: *Patents / *Valves / *Closures / *Fuel air explosives / Seals(Stoppers) / Interfaces / Explosives / Pistons
Uncontrolled terms: PAT-CL-89-1 / NTISGPN

AD-A061 879/15L NTIS 79019351
Chemical Initiation of FAE Clouds
von Elbe, G.; McHale, E. T.
Atlantic Research Corp Alexandria VA Combustion Technology Group
400716)
Annual Interim rept. May 77-Sep 78, Rept no: ARC-47-5711, 13 Oc 78, 21p, Contract: F049620-77-C-0037, Monitor: AFOSR-TR-78-1473
NTIS Prices: PC A02/MF A01

It is believed that the second-event system in FAE devices can b eliminated by development of a process in which very rapid fue dispersion and simultaneous combustion are initiated by a singl event. According to this concept, a central explosive charge woul drive a highly reactive chemical agent such as chlorine trifluorid (ClF) into a surround of hydrocarbon fuel, with the effect that th fuel would be explosively dispersed and burned in the ambient air, an a FAE blast generated. Laboratory research is described in which smal slugs of CTF and BTF (bromine trifluoride) were driven pneumaticall into Diesel oil. The ensuing event was diagnosed by high speed motio pictures and blast gages. An FAE effect was reproducibly observed wit BTF. With CTF it was found that the agent-fuel reaction is so rapi that a counterforce develops at the interface of the liquids an prevents thorough mixing and reaction. In larger-scale field test that are planned, CTF will be explosively driven into Diesel oil, thu eliminating this hindrance. It is considered that proof of concept ha been demonstrated in the sense that a blast wave has been produced b chemical initiation of a fuel-air-mixture. The concept depends o rapid fuel dispersal accompanied by combustion. These aspects of th concept are scale-dependent

FLD: 19A, 19D, 79A, 79E
Controlled terms: *Fuel air explosives / *Detonations / Dispersing Diesel fuels / Chlorine trifluoride / Explosive actuators / Blas waves / Entrainment / Mixing / Photographic analysis
Uncontrolled terms: NTISDODXA

AD-A057 017/1SL NTIS 79000220
Summary of Work on Initiation, Combustion and Transition to Detonation in Homogeneous and Heterogeneous Reactive Mixtures
Strehlow, Roger A.; Barthel, Harold O.; Krier, Herman
Illinois Univ At Urbana-Champaign Dept of Aeronautical and Astronautical Engineering (173005)
Interim rept. 1 Jun 77-31 May 78, Jun 78, 23p, Grant: AFOSR-77-3336, Project: 2308, Task: A2, Monitor: AFOSR-TR-78-1151, NTIS Prices: PC A02/MF A01

The research deals with the broad topics of initiation, combustion and transition to detonation in homogeneous and heterogeneous reactive mixtures. One specific area deals with analytical and experimental work directed to direct initiation of detonation by a nonideal blast wave in chemically sensitized reactive fuel-air clouds. The other specific topic involves the hydrodynamic modelling of ignition and flamespreading in granular energetic solids to predict the potential for deflagration-to-detonation (DDT)

Fld: 19A, 21B, 19D, 79A, 79E, 81A
Controlled terms: *Fuel air explosives / *Explosives initiators / *Combustion / *Detonations / Mixtures / Homogeneity / Heterogeneity / Transitions / Deflagration / Reaction kinetics / Blast waves / Propelling charges / Propellant grains / Sparks / Pulsed lasers / Capacitance / Exploding wires
Uncontrolled terms: NTISDODXA

AD-A057 743/6SL NTIS 78057373
Critical Injection Velocities for Ignition
Kinney, G. F.; Sewell, R. G. S.
Naval Weapons Center China Lake Calif (403019)
Technical publication, Rept no: NWC-TP-6030, Jun 78, 21p, Project: RR00001, F32395, Task: RR0000101, Monitor: 18, NTIS Prices: PC A02/MF A01

Forcible injection of combustible material into a closed volume of air can increase its temperature substantially either by molecular impaction on a blunt face of an object or by its kinetic energy loss on sudden deceleration. Injection velocities required to produce ignition temperatures by each mechanism have been computed for a variety of combustible and explosive materials. The two diverse methods of computation are in rough agreement, with representative velocities for ignition being perhaps 1,000 m/s or somewhat less, corresponding to Mach numbers of about 2 1/2. Injection velocities required for the prompt initiation of the explosion of an explosive fuel are rather comparable, and delayed initiation can occur with somewhat lesser velocities. Calculations are all speculative in nature, but they provide a solid basis for comparison of fuels and for subsequent refinement by data from experimental results. (Author)

Fld: 21B, 21D, 19A, 79A, 81A
Controlled terms: *Ignition / *Fuel injection / *Explosives / Combustion / Chemical compounds / Flash point / Velocity / Molecul

AD-D001 993/2SL NTIS 78054412
FAX Canister with a Bottom Burster Charge and Dispersion Control Ring
Manning, Larry G.; Zabelka, Richard J.
Department of the Navy Washington D C (110050)
Patent, Rept no: PAT-APPL-560 377, PATENT-4 074 623, Filed 21 Jun 66, patented 21 Feb 78, 3p, Monitor: 19, Supersedes PAT-APPL-560 377-66, Availability: This Government-owned invention available for U.S. licensing and, possibly, for foreign licensing. Copy of patent available Commissioner of Patents, Washington, DC 20231 $0.50, NTIS Prices: Not available NTIS

The patent describes a cylindrical canister for producing a frusto-conical aerosol explosive cloud, having a frangible upper wall portion which fails first, producing a generally pancake shaped cloud, and a thickened control ring surrounding its lower wall portion which fails last, producing an upward and outward component to the pancake cloud. (Author)

Fld: 19A, 79A, 90I
Controlled terms: *Patents / *Fuel air explosives / Explosion effects / Shape / Aerosols
Uncontrolled terms: PAT-CL-102-6 / NTISGPN

AD-A056 464/1SL NTIS 78051093
The Effects of Physical and Chemical Processes on Two-Phase Detonations
Lu, Pai-Lien; Slagg, Norman; Fishburn, Barry
Army Armament Research and Development Command Dover NJ (393011)
Jun 78, 14p, Monitor: 18, NTIS Prices: PC A02/MF A01

Systematic studies of the effect of additives and fuel drop size on the detonability of heptane-air mixtures have been carried out under controlled laboratory conditions and in large scale field tests. It was shown in the shock tube studies that n-propyl nitrate and butyl nitrite as well as, to a lesser extent, small drop size can greatly widen the detonation limits and reduce initiation requirements of heptane-air mixtures. Large scale field tests of explosively disseminated fuel-air clouds confirm findings obtained in the laboratory tests, demonstrating that systematic laboratory tests can be used to predict detonability and performance of any new fuel system to be used in FAE munitions. Unique schlieren photographs of the reaction zone of propagating fuel-air detonations have been successfully obtained. No blast waves are observed either in the wave of single shocked fuel drops or from drops in the reaction zones of propagating detonations with air. Apparently, the assumption that such blast waves are necessary to maintain a two-phase detonation, is incorrect. Sensitized heptane is potentially superior to fuels used in current FAE munitions, providing increased explosive performance (larger area coverage per unit weight of fuel), greater safety in transport and handling and lower procurement costs

Fld: 13A, 19D, 79A, 79E
Controlled terms: *Fuel air explosives / *Heptanes / *Detonations / Additives / Nitrates / Nitrites / Butyl radicals / Propyl radicals / Drops / Air / Schlieren photography
Uncontrolled terms: NTISDODXA

PB-278 267/0SL NTIS 78027970
Evaluation of the Application of Repetitive Fuel/Air Explosions to Rock Ripping. Evaluation and Durability Testing of a Staged Combustion Rock Ripper. Phase II
Colburn, John W. Jr
Southwest Research Inst., San Antonio, Tex. Dept. of Engine and Vehicle Research.*Bureau of Mines, Washington, D.C
Final rept. Apr 75-Jun 76, 15 Apr 77, 96p, Contract: H0252056, Monitor: BuMines-OFR-15(2)-78, See also Final rept. on Phase 1, PB-278 266, NTIS Prices: PC A05/MF A01

A tractor-integrated version of an explosive ripping system was developed for mining application. This system uses diesel fuel and a tractor-mounted blower supplying 30 psig compressed air to a two-stage combustion chamber to produce a high-pressure (600 psia) gas charge. The charge is rapidly released into the rock formation near the tip of the ripper. The system, mounted on a D9 tractor, was tested at several quarry and mining operations to investigate rock fracturing effectiveness. Although the results of comparative ripping passes conclusively demonstrated that the system increases rock fracture, performance of the system is strongly dependent on rock morphology and properties as well as basic performance of the tractor-ripper. The theory of conventional and explosive ripping modes is described, and existing correlations of seismic velocity and ripper performance are shown to be in error

FIJ: 8I, 13B, 13C, 19A, 48A, 50B, 50C, 79A
Controlled terms: *Bulldozers / *Rock excavation / *Explosives / Production rate / Explosions / Feasibility / Rock mechanics / Fracturing
Uncontrolled terms: *Fuel air explosives / NTISDI2M

PB-278 266/2SL NTIS 78027969
Increased Economy of Dozing Operations Using Controlled Fuel/Air Explosions. Evaluation and Durability Testing of a Staged Combustion Rock Ripper. Phase I
Colburn, John W. Jr; Melton, Rosser B. Jr
Southwest Research Inst., San Antonio, Tex. Dept. of Engine and Vehicle Research.*Bureau of Mines, Washington, D.C
Final rept. Apr 75-Feb 76, 30 May 77, 55p, Contract: H0252056, Monitor: BuMines-OFR-15(1)-78, See also Final rept. on Phase 2, PB-278 267, NTIS Prices: PC A04/MF A01

Enhancement of bulldozing production rate through the use of fuel-air explosions for soil displacement was studied using scale-model testing. It was concluded that the process is applicable to conventional bulldozing as well as side-casting, and that it is technically feasible as well as economically attractive. Further development work is recommended for the construction of a full-size unit for evaluation

FIJ: 13B, 13C, 8I, 19A, 50B, 50C, 48A, 79A

AD-913 443/3SL NTIS 73027632
Fundamental Aspects of Unconfined Explosions
Nicholls, J. A.; Sichel, M.; Fry, R. S.; Hu, C.; Glass, D. R.
Michigan Univ Ann Arbor Dept of Aerospace Engineering (402 605)
Final rept. 22 Jan 72-21 Jan 73, Jun 73, 156p, Contract F08635-71-C-0083, Project: AF-2513, Task: 251307, Monitor AFATL-TR-73-125, Distribution limitation now removed, NTIS Prices PC A08/MF A01

This report covers progress made in the second year of the researc program. The first part of the report is devoted to a generalize analytical prediction of the ground impulse that can be obtained fro a blast wave, detonation wave, and an idealized fuel-air explosion The latter consists of blast wave behavior for radius, r, less than critical radius, r*, and Chapman-Jouguet detonation for r > r*. In al cases so far, the finite diameter of the cloud with the attendan shock wave propagation beyond the cloud has not been taken int account. The latter part of this report is devoted to the experimenta aspects. Improvements in the facility for generating cylindrical shoc waves and detonation waves are described controlled experiments o cylinderical blast waves with the associated data reduction technique are discussed. The results are interpreted to yield a calibration o the effective energy release of the initiating charge of Detasheet Two phase cylindrical detonation experiments were also conducted usin a highly refined fraction of kerosene. The results indicate that a small radius blast wave behavior predominated whereas at larger radiu a constant velocity detonation was realized when the initiation energ was sufficiently high. The experimentally determined transition radiu between the two types of behavior agreed very well with theoretica values. Cylindrical detonations in gaseous MAPP-air mixtures were als studied. The variation in threshold energy required for initiation a well as rich and lean limits were established. The results agree ver well with large scale field tests. (Author)

FLD: 19A, 7D
Controlled terms: (*Explosives / *Gases) / (*Explosions Mathematical analysis) / Explosion effects / Mathematical prediction Ground effect / Shock waves / Detonations / Fuels / Air / Blast Kerosene / Calibration / Effectiveness / Energy / Velocity Explosives initiators / Hydrocarbons / Detonation waves / Alkynes Propenes / Dienes
Uncontrolled terms: Fuel air explosives / Mapp(Methylacetylene-prop adiene) / NTISDODXD

AD-A051 354/35L NTIS 78026637
Mechanisms of Initiation of Detonation in Explosive Vapor Clouds
Knystautas, R.; Lee, John H.
McGill Univ Montreal (Quebec) Dept of Mechanical Engineering (223165)
Final rept. 1 Jan-31 Dec 77, 1978, 41p, Grant: AFOSR-77-3277, Project: 2308, Task: A2, Monitor: AFOSR-TR-78-0456, Presented at Colloquium on Gas Dynamics (6th), Stockholm (Sweden), Aug 77, NTIS Prices: PC A03/MF A01

During this period emphasis has been placed mostly on problems pertaining to feasibility of FAE III weapons. In particular major efforts have been devoted to the study of the mechanisms of initiation using various techniques other than the blast initiation method via concentrated explosive charges of conventional FAE weapons. Perhaps the most significant progress is the discovery of the universal initiation mechanism of Shock Wave Amplification by Coherent Energy Release (SWACER). When conditions for the SWACER mechanism to work have been generated locally in the explosive gas, then initially weak shocks can amplify extremely rapidly to form detonations in a time scale of the order of microseconds and corresponding length scales of the order of centimeters for the sub-atmospheric fuel-oxygen mixtures studied. It has been demonstrated experimentally that flash photolysis, intense turbulent mixing of either a pyrophoric compound (DMZ) or hot combustion products with the explosive gas can lead to direct initiation via the SWACER mechanism. Theoretical modelling of the SWACER mechanism is being performed to achieve the necessary criteria for scaling up the present laboratory scale experiments to field tests and to the use of fuel-air mixtures rather than the more detonable fuel-oxygen mixtures of the present work. (Author)

Fld: 19D, 19A, 79E, 79A
Controlled terms: *Fuel air explosives / *Detonations / Shock waves / Combustion products / Pyrophoric materials / Photochemical reactions
Uncontrolled terms: Shock Wave Amplification by Coherent Energy Release / SWACER(Shock Wave Amplification by Coherent Energy Release) / FAE 3 weapons / NTISDODXA

AD-A048 794/2SL NTIS 79013036
A New Simulation Facility for Atomic Explosions-Project FAX. Phase II-Definition and Design of Experimental Facility
Morrison, R. B.; Oliver, R. W.
McMillan Science Associates Inc Los Angeles Calif (391164)
Final rept. 25 Mar-31 Oct 76, Rept no: MSA-FCR-18-DNA, 31 Oct 76, 101p, Contract: DNA001-76-C-0271, Project: Y99QAXS, Task: D070, Monitor: AD-E300-366, See also Phase 1, AD-A048 793, NTIS Prices: PC A06/MF A01

This study defines the user requirements for a fuel-air explosive test facility for nuclear blast simulation. It details an experimental program and provides the design for an initial experimental fuel-air explosive facility with a capacity of 10,000 pounds of fuel which, by making use of its design as a basic cell, may be expanded to a full 1-KT nuclear blast simulation facility with a 200,000-pounds fuel capacity. (Author)

Fld: 19D, 19A, 79A, 79E
Controlled terms: *Nuclear explosion simulation / *Fuel air explosives / Simulators / Blast / Blast waves / High explosives / Dispersing / Detonations / Overpressure / Blast loads / Tanks(Combat vehicles) / Aircraft / Mortars / Artillery / Military vehicles / Test facilities
Uncontrolled terms: FAX project / Blast simulation / Simulation facilities / NTISDODXA

AD-A048 793/4SL NTIS 78013035
A New Simulation Facility for Atomic Explosions (Project FAX) Phase I-Preliminary Engineering Feasibility
McMillan, W. G.; Oliver, R. W.; McMillan, H. C.
McMillan Science Associates Inc Los Angeles Calif (331154)
Final rept, 5 Mar-30 Aug 75, Rept no: MSA-FCR-13-DNA, 30 Aug 75, 80p, Contract: DNA001-75-C-0263, Project: Y99CAXS, Task: G602, Monitor: AD-E300-065, See also Phase 2, AD-A048 794, NTIS Prices: PC A05/MF A01

This study investigates the feasibility of using unconfined fuel-air explosions to simulate the balst effects of up to one kiloton nuclear explosions. The detailed theoretical physico-chemical calculations of this study along with experimental observations from other sources show the feasibility of such simulation. Substantial savings in the cost of nuclear blast simulation as well as improved predictability are indicated by using a fuel-air explosion in lieu of HE or Ammonium Nitrate-Fuel Oil (ANFO). Preliminary engineering and hydrodynamic calculations for a re-usable fuel-air explosion facility are presented along with recommendations for further engineering design developments in the several methods described which will achieve the desired fuel-air explosion. (Author)

FLD: 19D, 13A, 79A, 79D
Controlled terms: *Nuclear explosion simulation / *Fuel air explosives / Simulators / Blast / Blast waves / High explosives / Dispersing / Test facilities / Feasibility studies / Cost analysis / Thermochemistry
Uncontrolled terms: FAX project / Blast simulation / Simulation facilities / Design / NTISDODXA

AD-A043 003/3SL NTIS 78010532
Analysis of Ground Motion Data and Prediction Techniques from the Pre-DICE THROW II Events
Perry, Gerald L. E.; Hudson, Craig C.; Loring, Bruce P.
General Electric Co Albuquerque N Mex TEMPO (409448)
Final rept. Jan 76-Mar 77, Mar 77, 239p, Contract: DNA001-75-C-0023, DNA001-76-C-0376, Project: P99QAXD, Task: E910, Monitor: SBIE-AD-E300-051, NTIS Prices: PC A12/MF A01

Twenty-five experimenters and support agencies participated in the pre-DICE THROW II program. This program consisted of two HE events, one using a 100-ton surface-tangent sphere of TNT and the other a 120-ton surface-tangent domed cylinder of bagged ANFO. The purpose of this report is to compare certain aspects of the ground-motion data with the predictions made of these aspects before the tests. Four agencies were charged with providing predictions: Air Force Weapons Laboratory; Waterways Experiment Station R and D Associates and Field Command, DNA. This report consists of seven chapters, which include: A brief description of the initiation of ground motion under a high-explosive detonation ground-motion transducers, canisters, grout and prediction methods; summaries of the data from Events 1 and 2 and comparisons of these with the predictions; analysis and authors' conclusions. (Author)

FId: 19D, 19A, 79A, 79E
Controlled terms: *Explosion effects / *High explosives / *Ground motion / Fuel air explosives / Ammonium nitrate / Cratering / Displacement / Transducers / Velocity / Mathematical prediction / TNT / Data acquisition / Tables(Data) / Waveforms / Wave propagation / Nuclear explosion simulation / Blast waves / Seismic waves / Grout
Uncontrolled terms: High explosive tests / Pre-DICE throw shot 2 / Prediction techniques / NTISDODXA

AD-A047 605/1SL NTIS 78003357
FAE Flow Computations Using AFAMF Code
Kiwan, Abdul R.
Ballistic Research Labs Aberdeen Proving Ground Md (050750)
Rept no: BRL-1547, Sep 71, 11p, Project: 1T061102A14B, Monitor: 18, NTIS Prices: PC A02/MF A01

This report explains how one may use the AFAMF code to compute approximately the flow arising from the detonation of a cloud of fuel air mixture. A scaling method is given to effect a comparison o computed results with experimentally measured values. (Author)

FId: 19D, 19A, 79A, 79E
Controlled terms: *Fuel air explosives / *Detonation waves Mathematical models / Flow fields / Clouds / Spheres / Fuel air rati / Simulation / Computations / Finite Difference theory / Cloud physic / Surface properties / Rarefaction / Wave propagation / Scalin factors
Uncontrolled terms: NTISDODXA

AD-A047 585/5SL NTIS 78003337
Explosion Hazards Associated with Spills of Large Quantities o
Hazardous Materials. Phase II
Lind, C. D.; Whitson, J. C.
Naval Weapons Center China Lake Calif (403019)
Final rept, Nov 77, 40p, Contract: DOT-CG-34035-A, Monito:
USCG-D-85-77, See also Phase 1, AD-A001 242, NTIS Prices: PC A03/
A01

This report documents the results of Phase II of a program aimed
quantifying the explosion hazards associated with spills of lar
quantities of hazardous material such as liquefied natural gas a
liquefied petroleum gas. The principal results of this phase of t
work are: a quantitative empirical description of the burning behavi
in fuel-air mixtures, an examination of flame acceleration processe
the observation that, in 17 large scale burn tests, no transition
detonation occurred, and that methane-air mixtures cannot be detonat
with moderate size solid explosive boosters. (Author)

Fld: 19D, 21D, 79E, 97K, 85D
Controlled terms: *Hazardous materials transportation / *Fuel a
explosives / *Liquefied natural gas / Vapors / Accidents / Spilling
Deflagration / Detonations / Hazards / Fuel air ratio / Burning rate
Waterways / Water traffic / Flame propagation / Flammability / Te
methods / Explosions / Explosive gases
Uncontrolled terms: Vapor clouds / NTISDODXA / NTISDOTCG

AD-A047 385/0SL NTIS 78008137
Application of FAE Technology to the Design of Nuclear Airbl
Simulation Experiments
Sauer, F.; Stubbs, T.
Physics International Co San Leandro Calif (282760)
Final rept. Sep 76-Feb 77, Rept no: PIFR-978, Aug 77, 6
Contract: DNA001-76-C-0354, Project: Y990AXS, Task: D070, Monit
SBIE-AD-E300025, NTIS Prices: PC A04/MF A01

The detonation of fuel aerosols and vapors in air is investiga with respect to the applicability of this type of explosion generating an airblast simulation a 1-KT nuclear airburst explosi Extensive investigations into existing overpressure overpressure-impulse data from weaponized FAE's and carefu controlled hemispherical balloon detonations has allowed a compari of the fuel-air explosives with both condensed explosives (TNT nitromethane) and a predicted 1-KT nuclear surface burst. It was fo that, depending upon cloud geometry, the total fuel required fo 1-KT nuclear airblast simulation varied between 63 and 200 tons. concentration of fuel in air must be close to stoichiometric and mean droplet diameter must be 2500 microns or less. Investigation existing nozzles indicate that it is questionable whether commercia available nozzles can project a vapor to the requisite height for 1-KT simulation. Various fuel candidates were investigated. prop-hydrocarbon compounds are attractive with higher c hydrocarbons being worth consideration. (Author)

Fld: 19D, 19A, 19C, 79A, 79E
Controlled terms: *Fuel air explosives / *Blast / Nuclear exples simulation / High explosives / Detonations / Air / Fuels Hydrocarbons / TNT / Nitromethane / Nozzles
Uncontrolled terms: Airblast / Blast simulation / NTISDCDXA

AD-A046 726/6SL NTIS 78004333
Abstracts 1977 AFOSR Contractors Meeting on Air-Breathing Combust
Dynamics. September 12 - 13, 1977
Purdue Univ Lafayette Ind School of Mechanical Engineering (292
Interim rept, 15 Sep 77, 129p, Grant: AFOSR-76-2936, Proje
2308, Task: A2, Monitor: AFOSR-TR-77-0058, NTIS Prices: PC A0
A01

The report consists of a collection of abstracts of the ouse research progress reports given by AFOSR contractors and of inv papers from other governmental agencies and contractors. These pa presented over a five-day period composed the 1977 annual contrac meeting on air-breathing combustion dynamics. The princ investigators and their organizational association are identified. (Author)

Fld: 21B, 21A, 21E, 81D, 81A
Controlled terms: *Combustion / *Air breathing engines / *Dynamic Supersonic combustion / Ignition / Detonations / Fuel air explosive Combustion stability / Heterogeneity / Homogeneity / Catalys

AD-A045 740/3SL NTIS 79000368
A Simplified Version of the Barthel Model For Transverse Wave Spacings in Gaseous Detonation
Chiu, K. W.; Lee, J. H.
McGill Univ Montreal (Quebec) Dept of Mechanical Engineering (223155)
8 Jun 75, 11p, Grant: AFOSR-72-2387, NRC-A3347, Monitor: AFOSR-TR-77-0560, Availability: Pub. in Combustion and Flame v26 p353-361 1976, NTIS Prices: PC A02/MF A01

The acoustic theory of Barthel and Strehlow for transverse wave spacing prediction is investigated in one-dimensional detonation waves. Based on a simple model in which heat is released uniformly in the reaction zone, the cell spacings are found to be dependent upon the following parameters: the induction zone length, reaction zone length, Mach number and specific heat ratio. For high pressures, further simplification can be made when the reaction zone length is negligible compared to the induction zone length. With only the induction time data, the cell spacings were calculated for steady or overdriven detonations in H2-O2 mixtures for various initial pressures and Ar dilution. The results are found to be in satisfactory agreement with experiments and with the more complex theoretical calculations of Barthel using the full chemical kinetics scheme for H2-O2 reaction. (Author)

Fld: 21B, 7D, 21A, 99F
Controlled terms: *Fuel air explosives / *Detonation waves / *Detonations / Combustion / Specific heat / Mach number / Reaction kinetics / Hydrogen / Oxygen / High pressure / Reprints
Uncontrolled terms: NTISDODXR

AD-A045 352/2SL NTIS 77052301
Defense Systems Management Review. Volume I. Number 4
Kelly, Albert J.; Gansler, Jacques S.; Brown, William F.; Lurcott Eugene; Bowen, James A.
Defense Systems Management Coll Fort Belvoir Va (410036)
Quarterly periodical rept. 1 Jul-30 Sep 77, 3 Oct 77, 91p, Monitor: 18, NTIS Prices: PC A05/MF A01

Contents: Can Weapon System Procurement Be Managed; A New Dimension in the Acquisition Process; Tailoring Program Requirements; F2D2, a System Management Tool; Observations on Defense Acquisition; Zero-Base Budgeting and Sunset Legislation; The Army Budget and Combat Capability; Establishing the FAE II; and Computer System Simulation--a design evaluation tool

Fld: 15E, 5A, 74E
Controlled terms: *Systems management / *Military procurement / Periodicals / Defense planning / Weapon systems / Acquisition / Combat effectiveness / Military budgets / Management planning and control / Flow charting / Functional analysis / Scheduling / Planning programming budgeting / Army budgets / Fuel air explosives / Compute

AD-A042 101/6SL NTIS 77039116
On the Effective Energy for Direct Initiation of Gaseous Detonations
Knystautas, R.; Lee, J. H.
McGill Univ Montreal (Quebec) Dept of Mechanical Engineering (223165)
9 Sep 75, 10p, Grant: AF-AFOSR-2387-72, Project: 9711, Task: 02, Monitor: AFOSR-TR-77-0537, Availability: Pub. in Combustion and Flame 27 p221-228 1976, NTIS Prices: PC A02/MF A01

The present paper demonstrates that the effective and hence the true critical energy E(c) for direct initiation of gaseous detonations using electrical sparks corresponds to the total energy deposited into the gas up to the time t(F) of th peak averaged power, i.e., (E(t)/t)max, of the spark. The energy subsequent to this time is found to have no noticeable influence on the initiation processes. The method for demonstrating this experimentally is via the 'crowbarred' discharge which was used to initiate cylindrically expanding detonation waves. Almost all previous investigations had implied that the direct initiation process can be characterized by a unique critical value of the source energy where the source energy was invariably taken as the total energy initially stored in the source or its equivalent. The present results indicate that the critical energy E(c) is non unique but depends on its rate of depositon. It is found that E(c) increases very rapidly with increasing time of energy deposition t(F). However, a minimum limiting value of the critical energy is found to exist as t(F) goes to 0. The present results, in fact, suggest that the direct initiation process should be characterized by two parameters, namely, the peak power of the source and the energy release up to the peak power. The critical peak averaged power of the source, i.e., P(c) = E(c) (t(f))/t(f), also exhibits a minimum value which corresponds to shock strengths of the order of the auto-ignition limit for the explosive mixture

Fld: 13A, 7D, 79A, 93F
Controlled terms: *Detonations / *Spark ignition / Explosions / Gases / Blast waves / Fuel air explosives / Spheres / Canada / Reprints
Uncontrolled terms: NTISDODXR

AD-A042 199/3SL NTIS 77033115
Influence of Electrode Geometry and Spacing on the Critical Energy for Direct Initiation of Spherical Gaseous Detonations

Matsui, H.; Lee, J. H.
McGill Univ Montreal (Quebec) Dept of Mechanical Engineering (223155)

15 Sep 75, 6p, Grant: AF-AFOSR-2387-72, Project: 9711, Task: 02, Monitor: AFOSR-TR-77-0593, Availability: Pub. in Combustion and Flame, v27 p217-220 1976, NTIS Prices: PC A02/MF A01

The paper reports experimental results on the critical energies for direct initiation of spherical detonations using electrical sparks under various electrode geometries and spacings. The results indicate that for large spacings the detailed electrode configurations have no influence on initiation energy. The critical energy per unit length reaches a minimum asymptotic value corresponding to the value found previously for cylindrical detonations. For electrode spacing less than the characteristic explosion length, the electrode geometry has an effect on the initiation energy. The flanged and the pointed needle electrodes form the lower and upper bounds, respectively, for the critical energy for various electrode configurations. For the case of the flanged electrode, significant increase in the critical energy occurs only when the spacing is less than the transverse wave spacing for the mixture itself. For small spacings the critical energy for pointed electrodes corresponds to the value for laser sparks obtained previously, indicating the approach to spherical symmetry. The results indicate that the effects of the electrode geometry are essentially those corresponding to the severity of gasdynamic expansion generated. The gasdynamic effects fall between the cylindrical and spherical symmetries. (Author)

FLD: 19A, 7D, 79A, 99F
Controlled terms: *Detonations / *Spark ignition / Explosions / Gases / Blast waves / Fuel air explosives / Electrodes / Gas dynamic / Geometry / Reprints / Spheres / Canada
Uncontrolled terms: NTISDODXR

AD-A041 504/2SL NTIS 77037030
Photochemical Initiation of Detonation in Gaseous Explosive Media
Knystautas, R.; Lee, J. H.
McGill Univ Montreal (Quebec) Dept of Mechanical Engineering (223155)
Final rept. 1 Jan 75-31 Dec 76, Jun 77, 80p, Grant: AF-AFOSR-2387-72, NSC-A6319, Project: 9711, Task: 02, Monitor: AFOSR-TR-77-0776, NTIS Prices: PC A05/MF A01

During this investigation a study was made of photochemical initiation of detonation in gaseous explosive media. The study is judged relevant to the development of the single event third generation FAE weapons. The flash photolysis technique was used to investigate the mechanisms of photochemical initiation of detonative chemical reactions in sub-atmospheric explosive gaseous mixtures of H2-Cl2 and C2H2-O2 with and without NO2 sensitization. Results conclusively demonstrate the feasibility of initiation of detonation by the free radical mode of initiation

Fld: 7E, 19D, 99E, 79E
Controlled terms: *Fuel air explosives / *Detonations / *Photochemical reactions / Exothermic reactions / Free radicals / Photolysis / Deflagration / Blast waves / Barometric pressure / Vapors / Fuels / Photodissociation / Acetylene / Oxygen / Hydrogen / Chlorine / Nitrogen oxides
Uncontrolled terms: Canada / NTISDODXA

AD-A041 269/2SL NTIS 77036345
A Multiple Rocket Launcher Simulation. Report II
Christensen, Dean E.; Richardson, Robert L.
Army Missile Research and Development Command Redstone Arsenal Al Ground Equip/Missile Structures Directorate (410263)
Technical rept, Rept no: DRDMI-TL-77-3, 23 Feb 77, 94p, Project 1W362303A214, Monitor: 13, NTIS Prices: PC A05/MF A01

A multiple-launching simulation program was devised which fire rockets in real time from a multiple launcher mounted on transporter. This simulator was used to establish error budget input for general support rocket systems. Comparisons of the launch effect on system accuracies for various size rockets were conducted. Thi program has provided a means whereby a launcher concept may b developed which can effectively reduce the errors due to rocke unbalance and thrust misalignment

Fld: 19G, 79M
Controlled terms: *Rocket launching / *Computerized simulation Error analysis / Multiple operation / Accuracy / Alignment Spinning(Motion) / Rates / Fuel air explosives / Equations of motion Degrees of freedom / Mathematical models
Uncontrolled terms: Real time / NTISDODXA

AD-D001 218/7SL NTIS 77033389
Fundamental Aspects of Unconfined Explosions
Nicholls, J. A.; Sichel, M.; Fry, R. S.; Hu, C.; DeSaro, R.
Michigan Univ Ann Arbor Dept of Aerospace Engineering (402 605)
Final rept. 22 Jan 73-2 Feb 74, Aug 74, 96p, Contract: F08635-71-C-0083, Project: AF-2513, Task: 251307, Monitor: AFATL-TR-74-123, Distribution limitation now removed, NTIS Prices: PC A05/MF A01

Blast wave initiation of detonation in a completely homogeneous cloud is considered. The self similar character of strong blast waves and Chapman-Jouguet detonation waves is used to arrive at simplified closed form solutions for the generation of ground impulse and dynamic impulse, up to the time that the detonation arrives at the edge of the cloud. The dependence of impulse on fuel properties and cloud geometry is predicted. The influence of side relief at the top of the cloud is considered. Experimental studies are described which investigate the initiation, transition, and quasi-steady propagation processes associated with blast initiated, cylindrical detonation waves. Experiments were conducted with all gaseous and heterogeneous fuel-air mixtures wherein a specially designed sectored shock tube was employed. A complete volumetric range of MAPP (Methyl acetylene, propane, propadiene)-air mixtures was investigated. Some results of the breakup and ignition of single fuel drops, when subjected to strong blast waves, are presented. (Author)

Fld: 19D, 19A, 79E, 79A
Controlled terms: (*Explosions / *Fuel air explosives) / Mathematical models / Explosives / Clouds / Blast / Mechanical waves / Mixtures / Dynamic tests / Impulse loading / Detonations / Detonation waves / Geometry / Wave propagation / Shock tubes / Methyl radicals / Alkynes / Propane / Dienes / Ignition / Drops / Fuels / Theory / Pressure / Velocity / Distribution
Uncontrolled terms: *Unconfined explosions / Combustible mixtures / Chapman-Jouguet detonation theory / NTISDODXD

AD-B001 925/6SL NTIS 77033388
Dynamic Response of Structures and Materials to Impulsive Loads
Ross, C. Allen; Sierakowski, Robert L.; Malvern, Lawrence E.
Florida Univ Gainesville Dept of Engineering Science and Mechanic
(133 925)
Final rept. 17 Oct 73-30 Jun 74, Jul 74, 93p, Contract F08635-74-C-0036, Project: AF-2549, Task: 254902, Monitor AFATL-TR-74-120, Distribution limitation now removed, NTIS Prices PC A05/MF A01

This report is divided into three main subjects, e. g., bea response to impulsive loads of fuel-air explosions (FAE), effect c fuel-air explosions in confined unpressurized containers, and th effect of intense impulsive loads from surface blasts on materia removal and degradation of a concrete semi-half space. Investigatic into the response of small ductile beam elements subjected to blas loadings indicates a need for analysis of beams including gros deformation, axial constraints, and complete failure. The response c small beams to fuel-air explosions fall in a transition between static mechanism and a traveling plastic hinge mechanism. Equations c motion, based on a strength of material approach, are derived for bo mechanisms. The same general shock transmission and reflection c detonation waves are found to be operative in both confined a unconfined fuel-air explosions. The ratio of the reflected pressure the static pressure of a detonation wave is dependent only on t ratio of specific heats and reaches a maximum of 2.6 for a specif heat ratio of infinity. Computational models are available and ha been used with some success for prediction of cratering, materi removal and material degradation for certain rock media and could used for concrete; however, development of constitutive models f concrete is still in the fundamental stage. More fundamental researc especially experimental and theoretical work on materi characterization, is needed before a reasonable damage estimation concrete subjected to intense impulsive loads can be obtaine (Author)

FLD: 13M, 19D, 79E
Controlled terms: (*Beams(Structural) / Dynamic response) / *Impulse loading / Structural response) / Structural members / Fu air explosives / Blast loads / Concrete / Cratering Failure(Mechanics) / Overpressure / Stress strain relations / Hinges Plastic deformation / Radial stress / Plates / Deflection / Wa propagation / Equations of motion / Partial differential equations Impact tests / Impact prediction / Detonation waves / Confin environments / Tensile properties
Uncontrolled terms: NTISDODXD

AD-B001 492/7SL NTIS 77027067
The Plastic Response of Rectangular Membrane Plates to Mild Explosive Loading Functions
Strickland, William S.; Ross, Claudius A.
Air Force Armament Lab Eglin AFB Fla (409 936)
Final rept. Jun 73-Feb 74, Rept no: AFATL-TR-74-131, Nov 74, 41p, Project: AF-2549, Task: 254902, Monitor: 18, Distribution limitation now removed, NTIS Prices: PC A03/MF A01

This report presents the results of an effort to determine the failure of flat plates under mild impulsive loads typically found in fuel air explosions. Such failure may occur according to the criteria associated with stress wave propagation or due to an excessive deflection associated with the dynamic response of the plate. Using an energy method and a membrane model, a set of equations describing dynamic plate response are presented. Experimental observations and results of plate failure, along with pressure-time histories of controlled gas bag tests, are reported. In the case of ductile metals, such aluminum, mild steel, and some stainless steels used in aircraft, radar vans, etc., the elastic portion of the stress-strain curve is quite small, and the assumption of a rigid-strain-hardening constitutive relation appears to be quite realistic. A potential function representing the plastic work and based on an initial membrane stress and strain-hardening was developed for an assumed deflection curve. Using a generalized forcing function, based on actual pressure time histories for fuel air explosions, and this potential function, equations of motion were formulated using lagrangian methods. Assumed deflection curves which satisfied given boundary conditions were used, and the resulting non-linear differential equation was solved using an analog simulation program. The equation yields center point deflections, which is associated with a plate criterion based on maximum elongation of the material. Center point deflection predictions using this model are in good agreement with experimental results. Plate failure is initiated at the edge of the plate and is predictable using the ultimate strain of the material and the membrane model

Fld: 19D, 19A, 79E, 79A
Controlled terms: (*Blast loads / Flat plate models) / (*Fuel air explosives / Impulse loading) / Stress waves / Dynamic response / Failure(Mechanics) / Membranes / Plastic deformation / Fixed contacts / Elastic properties / Stress strain relations / Stress waves / Lagrangian functions / Mathematical models / Equations of motion / Nonlinear differential equations / Aluminum alloys / Steel / Stainless steel / Rectangular bodies
Uncontrolled terms: NTISDODXD

AD-D003 378/5SL NTIS 77013681
High Explosive Launcher System
Bilek, Andrew G.
Department of the Air Force Washington D C (109850)
Patent, Rept no: PAT-APPL-594 427, PATENT-3 999 482, Filed 9 Jul 75, patented 28 Dec 76, 6p, Monitor: 19, This Government-owned invention available for U.S. licensing and, possibly, for foreign licensing. Copy of patent available Commissioner of Patents, Washington, D.C. 20231 $0.50, NTIS Price: Not available NTIS

The patent relates to a cloud detonation initiator on a fuel-air-explosive (FAE) weapon in the form of a high-explosive retrolauncher attached thereto wherein a plurality of gun tubes each deploy an explosive grenade rearwardly to compensate for the forward motion of the FAE weapon. The grenades are essentially stopped in space as the cloud forms around them. The retrolauncher includes a plurality of different size charges in operative communication with a single chamber so that the velocity of the grenades can be controlled within a predetermined range by selectively detonating the charges singly and in combination

Fld: 19A, 79A, 99I
Controlled terms: *Fuel air explosives / *Explosives initiators / *Grenade launchers / *Patents / Delay elements(Explosive) / Explosive charges / Trajectories
Uncontrolled terms: PAT-CL-102-7.2 / NTISGPAF / NTISDODAF

AD-A035 489/4SL NTIS 77016011
AFOSR Contractors Meeting on Unconfined Detonations and Other Explosion Related Research (1976) Held at AF Armament Laboratory (AFATL) Eglin AFB, Florida on 13-14 December 1976
Ohio State Univ Research Foundation Columbus (267360)
Interim rept, Dec 76, 37p, Grant: AF-AFOSR-2511-73, Project: 2303, Task: A2, Monitor: AFOSR-TR-76-1110, NTIS Prices: PC A03/MF A01

The report consists of a collection of abstracts of the numerous research progress reports given by AFOSR contractors and of invited papers from other governmental agencies and CONUS and European contractors. These papers presented over a three day period composed the 1976 annual contractor's meeting on combustion dynamics associated with fuel-air explosion phenomena. The principal investigators and their organizational association are also identified. (Author)

Fld: 19A, 79A
Controlled terms: *Meetings / *Fuel air explosives / Abstracts / Reports / Ignition / Deflagration / Flameout / Combustion / Detonations / Explosions / Supersonic combustion / Homogeneity / Heterogeneity / Blast waves / Pyrophoric materials / Gun propellants
Uncontrolled terms: NTISDODXA

PATENT-3 955 509 NTIS 77015786
Fuel-Air Munition and Device
Carlson, G. A.
Energy Research and Development Administration
Patent, Rept no: PAT-APPL-809 440, Filed 21 Mar 69, patented 11 May 76, 9p, Monitor: 18, This Government-owned invention available for U.S. licensing and, possibly, for foreign licensing. Copy of patent available Commissioner of Patents, Washington, D.C. 20231 $0.50, NTIS Prices: Not available NTIS

An aerially delivered fuel-air munition is described. An impermeable tank is filled with a pressurized liquid fuel and joined at its two opposite ends with a nose section and a tail assembly respectively to complete an aerodynamic shape. On impact the tank is explosively ruptured to permit dispersal of the fuel in the form of a fuel-air cloud which is detonated after a preselected time delay by means of high explosive initiators ejected from the tail assembly. The primary component in the fuel is methylacetylene, propadiene, or a mixture to which is added a small mole fraction of a relatively high vapor pressure liquid diluent or a dissolved gas diluent having a low solubility in the primary component. (ERA citation 02:010977)

Fld: 19A, 79A, 90I
Controlled terms: *Chemical explosives / *Ordnance / Additives / Aerodynamics / Air / Design / Detonations / Fuels / Ignition / Mixing / Tanks
Uncontrolled terms: ERDA/450100 / *Patents / NTISGPERDA / NTISEPDA

AD-913 963/7SL NTIS 77014133
Detonability of Some Natural Gas-Air Mixtures
Vanta, Elizabeth B.; Foster, Joseph C. Jr; Parsons, Gary H.
Air Force Armament Lab Eglin AFB Fla (400 936)
Final rept, Rept no: AFATL-TR-74-80, Apr 74, 14p, Project: AF-2513, Task: 251307, Monitor: 18, Distribution limitation now removed, NTIS Prices: PC A02/MF A01

Seven mixtures (ranging from 5.2 to 12.5 percent by volume) of natural gas in air were screened for their detonability using a bag test method. Erratic, uneven detonations were initiated at the 8.6 to 8.8 percent concentration level, with explosive charges ranging from 1001 to 1020 grams. At all other tested fuel concentrations deflagrations occurred. Although the detonations successfully propagated the entire length of the bag, a steady Chapman-Jouguet type wave front was not observed. The experimental detonation velocities and minimum initiator weight requirements are compared to those obtained in other studies under similar experimental conditions. (Author)

Fld: 19A, 19D, 79A, 79E
Controlled terms: *Fuel air explosives / *Detonations / Explosive

AD-D003 305/05L NTIS 77014109
Speed Controlled Second Event Launcher
Wiedermann, Arne H.
Department of the Air Force Washington D C (199850)
Patent, Rept no: PAT-APPL-610 465, PATENT-3 992 995, Filed 4 Se 75, patented 23 Nov 76, 6p, Monitor: 18, Supersedes AD-D001 611 This Government-owned invention available for U.S. licensing and possibly, for foreign licensing. Copy of patent available Commissione of Patents, Washington, D.C. 20231 $0.50, NTIS Price: Not availabl NTIS

The patent relates to a variable position launcher including launch tube in which the second event (SE) package is placed. positioning spring on the explosive side of the SE package urges i toward the muzzle end of the tube which is sealed with a frangibl cover. A gas inlet operates to pressurize the muzzle end of the tub and apply a velocity dependent force on the SE package opposite th spring force so that the SE package opposite the spring force so tha the SE package is accurately positioned within the tube thereb controlling the retrolaunch velocity. The invention relates to liquid fuel air explosive device

Fld: 19A, 79A, 90I
Controlled terms: *Fuel air explosives / *Detonators / *Patents Launch tubes / Bursting charges / Speed regulators / Dela elements(Explosive)
Uncontrolled terms: PAT-CL-102-7.2 / NTISGPAF

AD-D003 156/7SL NTIS 77007760
Explosive Closure Valve
Lopez, Alvaro G.
Department of the Navy Washington D C (110050)
Patent Application, Rept no: PAT-APPL-706 869, Filed 19 Jul 76 7p, Monitor: 18, This Government-owned invention available for U.S licensing and, possibly, for foreign licensing. Copy of applicati available NTIS, NTIS Prices: PC A02/MF A01

The patent application relates to an explosive closure valve tha provides a fast acting seal at an explosive interface. The valve i attached to an interface wall. It operates such that a piston in th valve moves at right angles to the path of a detonating explosiv element thereby, positively blocking the hole by the expende explosive element. The invention is intended for use with a fuel-ai explosive system

Fld: 19A, 79A, 90I
Controlled terms: *Fuel air explosives / *Valves / *Pate applications / Closures / Pistons / Seals(Stoppers) / Detonating cor
Uncontrolled terms: PAT-CL-102-70 / NTISGPN

AD-912 430/6SL NTIS 76941991
Compatibility Test of CBU-55/B Munition on the A-37 Aircraft (SEEK EAGLE)
Rigdon, Vernon 3, Jr
Armament Development and Test Center Eglin AFB Fla (404 938)
Final rept, Rept no: ADTC-TR-73-49, Jul 73, 33p, Project: ADTC-335AA012, Monitor: 13, Distribution limitation now removed, NTIS Prices: PC$4.00/MF$3.00

The CBU-55/B munition has been certified on stations L3 and R3 of the A-37 aircraft for carriage and release up to 300 KIAS. This test was conducted to determine if the certification limits could be expanded to include stations L4 and R4, and increase the maximum release speed to 350 KIAS. Satisfactory physical fit was demonstrated in accordance with MIL-STD-1289 with the exception of ground clearance; however, this was considered acceptable since the clearance was greater than the already certified drop tanks on stations L2 and R2. Satisfactory carriage was demonstrated up to 413 KIAS and loads from -2.0 to +6.0 G. Certification limits could not be expanded to 350 KIAS; however, satisfactory separation was demonstrated to 325 KIAS in level flight on all stations and 300 KIAS in a 30-degree dive on stations L4 and R4

Fld: 1C, 19B
Controlled terms: (*Attack bombers / *Bomb ejectors) / Bomb racks / Jet bombers / Compatibility / Release mechanisms / Explosives / Explosive gases / Fuels / Air / Flight testing / Interfaces / Separation / Bomblets
Uncontrolled terms: *A-37 aircraft / *Cbu-55/b munitions / Fae(Fuel air explosives) / *Fuel air explosives / Seek eagle project / NTISDODXD

AD-??2 582/5GL NTIS 76?41281

Fundamental Aspects of Unconfined Explosions

Nicholls, J. A.; Fry, R. S.; Glass, D. R.; Sichel, M.; Vande: Schaaf, J.

Michigan Univ Ann Arbor Dept of Aerospace Engineering (402 603)

Final rept. 2? Jan 71-19 Jan 72, Rept no: 001389-2-T, Mar 72. 154p, Contract: F?8635-71-C-0083, Project: AF-2513, Task: 251307. Monitor: AFATL-TR-72-49, Distribution limitation now removed, NTI: Prices: PC$6.75/MF$3.00

The theoretical aspects of cylindrical strong blast waves an Chapman-Jouguet (C-J) detonations are treated in detail. A critica radius is discussed which divides the cloud into an inner blast wav zone and an outer detonation zone. Expressions for the evaluation o ground and dynamic impulse are presented, and the propagation of a C- detonation through a cloud of fuel drops, the initiation problem, an deviations from the ideal cylindrical blast model are considered. modified computer program for calculating detonation velocity o complex hydrocarbon fuels is discussed. The design and operation of a experimental facility to study the propagation of two-phas detonations in a cylindrical segment of a cloud is describe Experiments conducted with kerosene drops in air showed that at smal radius the cylindrical wave decayed as a shock wave, but beyond critical radius the wave becomes a constant velocity two-phas Chapman-Jouguet detonation. The experimentally determined critic radius agreed quite well with the theoretical predictions. The result lend encouragement to the prediction of threshold energy level required for detonation initiation in various geometries. (Author)

FldG: 19D

Controlled terms: (*Explosions / Mathematical models) / (*Detonati waves / Propagation) / Blast / Wave propagation / Aerosols / Clouds Shock waves / Fuels / Air / Liquids / Fuel sprays / Detonations Theory / Quenching / Drops / Hydrocarbons / Particle size / Particl trajectories / Velocity

Uncontrolled terms: Chapman-Jouguet equations / Fuel air explosive / Fuel clouds / NTISDODXD

AD-D002 673/7SL NTIS 76037894
Fuel-Air Explosive Bomblet
Glass, Cecil A.
Department of the Navy Washington D C (110050)
Patent, Rept no: PAT-APPL-472 760, PATENT-3 940 443, Filed 14 Ju 65, patented 21 Feb 76, 8p, Monitor: 13, This Government-owne invention available for U.S. licensing and, possibly, for foreig licensing. Copy of patent available Commissioner of Patents Washington, D.C. 20231 $0.50, NTIS Price: Not available NTIS

The invention relates generally to concussion-type or blast weapons and more particularly to a fuel-air explosive (FAX) bomblet fo establishing and subsequently detonating a fuel-air cloud at groun level, whereby large target areas may be effectively subjected to th damaging overpressure effects of a detonation velocity or shock wav generated through the detonation of the fuel-air cloud

Fld: 19B, 79C, 90
Controlled terms: *Fuel air explosives / *Bomblets / *Patents / Bo fuzes / Detonators / Bomb components / Shock waves
Uncontrolled terms: PAT-CL-102-6 / NTISGPN

AD-A021 755/4SL NTIS 76013011
Study of Dynamic Response of Shell Structures to Blast Loads
Ross, C. A.; Hilton, J. E.
Florida Univ Eglin AFB Graduate Engineering Center (407525)
Final rept. 19 Sep 74-30 Jun 75, Sep 75, 55p, Contract F08635-75-C-0022, Project: AF-2549, Task: 254902, Monito AFATL-TR-75-117, NTIS Prices: PC$4.50/MF$2.25

This report presents an effort to model the response of cylindric shells to fuel air explosions and mild high energy explosion. T different methods were used in the analysis. The first method assum small strain to derive the equation of motion using a force balan method. The second method was based on finite strain coupled with energy method using a Lagrangian formulation for the equations motion. Several equations of motion are derived for the finite stra case using several mode shapes for both full shell stiffness and ha shell stiffness. Spatial integration was performed by hand and t resulting equations of motions were solved numerically using a C 3600 MIMIC Source Language Program. (Author)

Fld: 13M, 79E
Controlled terms: *Shells(Structural forms) / *Blast loads *Structural response / Dynamic response / Fuel air explosives Strain(Mechanics) / Flat plate models / Equations of motion / Comput programs / Digital computers / Cylindrical bodies / Modes
Uncontrolled terms: CDC 3600 computers / Cylindrical shells NTISDODXA / NTISDODAF

N76-11299/4SL NTIS 76003907
Fuel-Air-Explosives. Explosions of Unconfined Vapour Cloud (Literature Survey)
Coevert, K.; Groothuizen, H. T.; Pasman, H. J.; Trense, R. W.
Technological Lab. RVO-TNO, Rijswijk (Netherlands)
Rept no: TL-1975-2, TDCK-65977, 24 Jan 75, 34p, Contract A73/KL/083-G-3372-II(3630), Monitor: 18, NTIS Prices PC$3.00/MF$2.25

A tentative evaluation of the problem of explosions of unconfine vapor clouds was made. The basic concepts of deflagrative an detonative combustion are reviewed and current research studies ar discussed, with particular regard to the blast wave generation b unconfined vapor cloud explosions

Fld: 19D, 21B, 79E, 81A
Controlled terms: *Deflagration / *Detonation / *Gas explosions *Vapors / Aerosols / Clouds / Flame propagation / Fuel combustion
Uncontrolled terms: NTISNASAE

N76-11261/4SL NTIS 76009786
Fuel Air Explosives. Flame Front Propagation of Gas Explosions, Par 1 Fuel Air Explosives. Vlamfrontuitbreiding Gasexplosies, Deelversla 1
Bosman, M.; Dejooijer, H.
Technological Lab. RVO-TNO, Rijswijk (Netherlands)
Rept no: TL-1975-3, TDCK-65976, 13 Jan 75, 13p, Contract A73/KL/083-G-3372-III, Monitor: 18, In Dutch; English Summary, NT Prices: PC$3.50/MF$2.25

Experiments were done with methane-air mixtures in a one cubic met explosion vessel as part of the investigations into the explosi properties of a free gas cloud. The expansion of the flame front w recorded photographically and compared with theoretically calculat values. With the mixtures used in the experiments, the flame veloci seemed to remain steady throughout the wake of the explosion, up to maximum expansion diameter of 30 cm where measurements were take (Author)

Fld: 19A, 19D
Controlled terms: *Air / *Flame propagation / *Gas explosions *Methane / Deflagration / Flammable gases / Fortran / High spe cameras / Photographic recording / Wakes
Uncontrolled terms: NTISNASAE

AD-D001 611/7SL NTIS 76005364
Speed Controlled Second Event Launcher
Wiedermann, A. H.
Department of the Air Force Washington D C (103850)
Patent Application, Rept no: PAT-APPL-610 465, Filed 4 Sep 75, 13p, Monitor: 18, Government-owned invention available for licensing. Copy of application available NTIS, NTIS Prices: PC$3.50/MF$2.25

The patent application relates to a variable position launcher including a launch tube in which the second event (SE) package is placed. A positioning spring on the explosive side of the SE package urges it toward the muzzle end of the tube which is sealed with a frangible cover. A gas inlet operates to pressurize the muzzle end of the tube and apply a velocity dependent force on the SE package opposite the spring force so that the SE package is accurately positioned within the tube, thereby controlling the retrolaunch velocity

Fld: 19A, 79A, 90
Controlled terms: *Fuel air explosives / *Detonators / Patents / Launch tubes / Bursting charges
Uncontrolled terms: PAT-CL-102-90 / *Patent applications / NTISGPAF

AD-D001 442/3SL NTIS 75004318
High Explosive Launcher System
Bilek, Andrew S.
Department of the Air Force Washington D C (103850)
Patent Application, Rept no: PAT-APPL-594 427, Filed 9 Jul 75, 14p, Monitor: 18, Government-owned invention available fo licensing. Copy of application available NTIS, NTIS Prices PC$3.50/MF$2.25

The patent application relates to a cloud detonation initiator on fuel-air-explosive (FAE) weapon in the form of a high-explosiv retrolauncher attached thereto wherein a plurality of gun tubes eac deploy an explosive grenade rearwardly to compensate for the forwar motion of the FAE weapon. The grenades are essentially stopped i space as the cloud forms around them. The retrolauncher includes plurality of different size charges in operative communication with single chamber so that the velocity of the grenades can be controlle within a predetermined range by selectively detonating the charge singly and in combination

Fld: 19A, 79A, 90
Controlled terms: *Fuel air explosives / *Detonators / Patents / Grenades / Gun launchers / Retrodirective steering
Uncontrolled terms: *Patent applications / PAT-CL-102-6 / NTISGPAF

AD/A-003 637/6SL NTIS 75007583
Effects of Propylene Oxide on Selected Species of Fishes
Crews, Richard C.
Air Force Armament Lab Eglin AFB Fla (400936)
Final rept. May-Sep 74, Rept no: AFATL-TR-74-133, Nov 74, 13p
Project: AF-5066, Task: 506601, Monitor: 18, NTIS Prices
PC$3.25/MF$2.25

In conjunction with the fuel air explosives testing and evaluatio program, laboratory investigations into the effects of propylene oxid were accomplished using two selected species of freshwater fishes an one marine species. For a 96-hour exposure period, the media tolerance limits (TLm) for propylene oxide were determined to be 14 ppm for mosquitofish (Gambusia affinis Baird and Gerard), 215 ppm fo bluegill (Lepomis macrochirus Rafinesque), and 89 ppm for commo mullet (Mugil cephalus Linnaeus). The results of these test demonstrate that the toxicity of propylene oxide is sufficiently hi to warrant caution with its handling near fresh-water or marir aquatic systems

FId: 6T, 6F, 93F, 57Y, 57H
Controlled terms: *Fuel air explosives / *Aquatic organisms *Fishes / Toxicology / Tolerances(Physiology)
Uncontrolled terms: *Propylene oxide / Marine fishes / Fresh wat fishes / Water pollution effects(Animals) / NTISDODAF

AD-783 253/3 NTIS 74039331
Agenda and Abstracts 1974 AFOSR Contractors Meeting on Unconfin Detonation and Fuel-Air Explosion Related Research Held at Eglin AF Florida on June 13-14, 1974
Strehlow, Roger A.
Illinois Univ Urbana Dept of Aeronautical and Astronautic Engineering (175005)
Interim rept, Jun 74, 46p, Grant: AF-AFOSR-2524-73, Projec AF-9711, Task: 971102, Monitor: AFOSR-TR-74-1284, NTIS Price PC$3.25/MF$2.25

The report consists of a collection of abstracts of the numero research progress reports given by AFOSR contractors and of invit papers from other governmental agencies and CONUS and Europe contractors. These papers presented over a two-day period composed t 1974 annual contractors meeting on combustion dynamics associated wi fuel-air explosion phenomena. The principal investigators and the organizational association are also identified. (Author)

FId: 19A, 19D, 79A, 79E
Controlled terms: *Detonations / *Fuel air explosives / *Meetings Explosions / Combustion / Deflagration / Supersonic combustio Combustion stability
Uncontrolled terms: NTISDODAF

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*         E S A    INFORMATION RETRIEVAL SERVICE            *
*                                                           *
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SER 772    DATE:09/05/91    TIME:17:02:29

               SEARCH HISTORY                                         PRINT SUMMARY
ST ITEMS DESCRIPTION                                        NO. FILE ACCN/SET FMT   ITEM-
 1   4817 EXPLOSIVES                                          1    2        3    4    1-
 2    259 FUEL(W)AIR
 3      3 1*2

 SRCH TIME      1.89  PRINT COUNT      8  DESCS.:          3
Copr. 1993 by the Amer. Chem. Soc.)
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096(13)071346 CHEMABS patent 96071346
Gelled FAE fuel
Wood, Stanley E.; Stull, Bertram O.
United States Dept. of the Navy
USA US
U.S.; (811121) P 3 pp.; In Eng; Coden: USXXA;
Pat. No.: 4302209; Int. Class: C10L-007/04; Nat. Class: 44-007/D ; Doc. Code: A;
Appl.: US 145512 800501;
Sections: 150002
Registry No.: 56-81-5 uses and miscellaneous <in propylene oxide, for fuel air explosives, with triethylene glycol for gelling optimization>; 75-56-9 uses and miscellaneous <fuels, for fuel air explosives, with silica gelling agents and alcohol mixture for gelling optimization>; 112-27-6 <in propylene oxide, for fuel air explosives, with glycerin for gelling optimization>; 7631-86-9 uses and miscellaneous <gelling agent, for propylene oxide for fuel air explosives with alcohol mixture for gelling optimization>
Mol. Formula: C3H8O3; C3H6O; C6H14O4; O2Si
Terms: fuel air explosive / propylene oxide air explosive / triethylene glycol air explosive / glycerin fuel air explosive
CT: EXPLOSIVES,<fuel air, from propylene oxide and silica gelling agent with alcohol mixture for gelling optimization>/GELATION,agents,-<silica, for propylene oxide for fuel air explosives, with alcohol mixture for gelling optimization>

096(06)037875 CHEMABS journal 96037875
Blast effect from a pancake-shaped fuel drop-air cloud detonation (theory and experiment)
Fishburn, B.; Slagg, N.; Lu, P.
U. S. Army Armament Res. Dev. Command Dover USA US NJ
J. Hazard. Mater.; (81) P 65-75; Vol 5; No 1-2; In Eng; Coden: JHMAD;
Sections: 150004
Terms: kerosine pancake cloud blast effect / fuel pancake cloud blast effect
CT: AIR,<explosive pancake shaped clouds, with fuels, blast effect of>/EXPLOSIVES,<fuel air pancake shaped clouds, blast effect of>/FUELS,<explosive pancake shaped clouds, with air, blast effect of>/KEROSINE,<explosive pancake shaped clouds, with air, blast effect of>

095(24)206332 CHEMABS patent 95206332
Gelled fuel-air explosive method
Stull, Bertram O.
United States Dept. of the Navy
USA
U.S.; (361031) P 2 pp.; In Eng; Coden: USXXAM
Pat. No.: 4233314; Class. No.: 44-7A; C10L7/00; Appl./Priority No.: 111453; Date: 110180;
Sections: 050003
Registry No.: 106-88-7 <explosives, for fuel air weapons>; 6028-57-5 <gelling agents, for butylene oxide for fuel air explosive weapons>; 7440-44-0 uses and miscellaneous <*>; 7631-86-9 uses and miscellaneous <*>
Mol. Formula: C4H8O; C9H16O2.1/3Al; O2Si
Terms: butylene oxide fuel air explosive
CT: EXPLOSIVES,<butylene oxide, for fuel air weapons>/compounds *

095(24)206318 CHEMABS report 95206318
Chemical initiation of FAE clouds
Von Elbe, G.; McHale, E. T.
Combust. Phys. Sci. Dep. Atl. Res. Corp. Alexandria USA VA
From: Gov. Rep. Announce. Index (U. S.) 1981, 81(14), 2926.
Document type: TECHNICAL REPORT; Report; (80) P 27 pp.; No AFOSR-TR-81-0255; Order No. AD-A096 415,; In Eng; Avail.: NTIS; Coden: GRREP;
Sections: 050003
Registry No.: 7787-71-5 <explosive, fuel air , chemical initiation of>; 7790-91-2 <*>
Mol. Formula: BrF3; ClF3
Terms: fluoride fuel air explosive / chlorine fluoride air explosive / bromine fluoride air explosive
CT: EXPLOSIVES,<fluoride fuel air, chemical initiation of>/FUELS,<explosive, fluoride air , chemical initiation of>

092(02)008507 CHEMABS journal 92008507
The use of fuel-air explosives as a nuclear blastwave simulator
Kratz, H. R.; Pierce, T. H.; Sedgwick, R. T.
Syst. Sci. Software La Jolla USA CA
Proc. Symp. Explos. Pyrotech.; (79) P Paper No. 18, 18 pp.; Vol 10th,; In Eng; Coden: PSEPD;
Sections: 050004
Registry No.: 75-56-9 uses and miscellaneous <fuel, for nuclear explosion blast wave simulation>
Mol. Formula: C3H6O
Terms: nuclear explosion blast wave simulator
CT: MODELS,physical,<for nuclear explosion blast waves, with propylene oxide air mixtures>/NUCLEAR EXPLOSION,<blast waves from, propylene oxide air mixtures in models for>/SHOCK WAVE,<from nuclear explosions, propylene oxide air mixtures for simulation of>

092(02)008492 CHEMABS journal 92008492
Fuel air explosives: a parametric investigation
Sedgwick, R. T.; Kratz, H. R.
Syst., Sci. Software La Jolla USA CA
Proc. Symp. Explos. Pyrotech.; (79) P Paper No. 33, 18 pp.; Vol 10th,; In Eng; Coden: PSEPD;
Sections: 050003
Registry No.: 74-82-8 uses and miscellaneous <fuel air explosives, feasibility of wide spread>; 75-56-9 uses and miscellaneous <*>; 142-32-5 uses and miscellaneous <*>; 544-16-1 <*>; 627-13-4 <*>; 7429-90-5 uses and miscellaneous <*>
Mol. Formula: CH4; C3H6O; C7H16; C4H9NO2; C3H7NO3; Al
Terms: fuel air explosive
CT: AIR,<explosives, for air bursts, feasibility of wide spread>/EXPLOSIVES,<fuel air compositions for, feasibility of wide spread>/GASOLINE,<fuel air explosives, feasibility of wide spread>/KEROSINE,<fuel air explosives, feasibility of wide spread>/esters

091(20)159839 CHEMABS patent 91159839
Fuel air explosive
Falterman, Charles W.; Bowen, James A.; Josephson, Larry H.
United States Dept. of the Navy
USA
U.S.; (120679) P 4 pp.; In Eng; Coden: USXXA;
Pat. No.: 4157928; Class. No.: 149-109.2; C06B23/00; Appl./Priority No.: 339662; Date: 010373;
Sections: 050003
Registry No.: 75-21-8 uses and miscellaneous <explosives mixture , containing propylene oxide, for cloud explosions>; 75-56-9 uses and miscellaneous <explosives mixtures , containing ethylene oxide for cloud explosion>
Mol. Formula: C2H4O; C3H6O
Terms: air ethylene propylene oxide explosive / alkylene oxide air explosives
CT: EXPLOSIVES,<ethylene oxide propylene oxide mixtures , for cloud explosions>

086(24)173774 CHEMABS journal 86173774
Some aspects of blast from fuel-air explosives
Fishburn, Barry D.
Feltman Res. Lab. Picatinny Arsenal Dover
Acta Astronaut.; (76) P 1049-65; Vol 3; No 11-12; In Eng; Coden: AASTC;
Sections: 050004
Terms: explosion blast wave flow
CT: DETONATION,<of fuel air explosives, numerical solutions for blast wave flow from>/DETONATION WAVE,blast,<from fuel air explosives, numerical solutions for>

[redacted]

#5

OFFICE OF THE UNDER SECRETARY OF DEFENSE

WASHINGTON, D.C. 20301-2000

25 March 1992
In reply refer to:
I-92/33662

POLICY

MEMORANDUM FOR DEFENSE INTELLIGENCE AGENCY
ATTENTION: MR. J. DEARLOVE
THROUGH: DIRECTOR TECHNOLOGY SECURITY OPERATIONS

SUBJECT: Request for Identification -- ACTION MEMORANDUM

(U) DTSA is currently working with the U.S. Customs Service in Minneapolis on their investigation of Honeywell. Information develop from this investigation indicates that the following [redacted] on numerous occasions. This individual [redacted]

(U)

Thanks for your help.

James K. Swanson
Foreign Affairs Specialist
Technology Security Operations

cc: Dave Seaver, DIA

Classified by: DIR/TSO
Declassify on: OADR

[redacted]

OFFICE OF THE UNDER SECRETARY OF DEFENSE

WASHINGTON, D.C. 20301-2000

POLICY

ODUSD(TSP)/DTSA/TSO
400 ARMY NAVY DRIVE
SUITE 300
ARLINGTON, VA 22202

FACSIMILE TRANSMISSION COVER SHEET

DATE: 25 March 1992

FROM: JAMES K. SWANSON
FOREIGN AFFAIRS SPECIALIST
TECHNOLOGY SECURITY OPERATIONS

(703) 693-1130
TELEPHONE

(703) 614-6392
UNCLASSIFIED FAX NUMBER

(703) 693-1130
STUIII

(703) 693-8355
DEDICATED STUIII FAX NUMBER

TO: Jim Dearlove
NAME

DIA
ORGANIZATION/ADDRESS

TELEPHONE NUMBER

FAX NUMBER

SUBJECT: Request for Identification

COMMENTS: Hi yer Jim

Jim

TOTAL NUMBER OF PAGES INCLUDING THIS PAGE: 2

[redacted] b(1) b(7) #7

Working Chronology
Fuel Air Explosives (FAE)
Iraq

.3.a.4/5 .3 b. [redacted]

Originator: CAPT James A. Huff, USNR

02 OCT 90 (TUE): [redacted]

(U) ~~(S/NF)~~ Reviewed open source information on Messerschmitt-Boelkow-Blohm (MBB). The sources of this information are (a) British Broadcasting Corporation (BBC) Panorama show (3 SEP 90), and (b) Der Speigel (24 SEP 90).

(U) ~~(S/NF)~~ Requested in-house data dump on key words FAE, Iraq, Bombs and MBB.

03 OCT 90 (WED): [redacted]

(U) ~~(S/NF)~~ Analysis of in-house data confirmed DIA's findings and conclusions. [redacted]

(U) ~~(S/NF)~~ Invited by Nancy Hindman, DTSA/M, to attend a meeting on 03 OCT 90 at 1330 on an [redacted]

[redacted]

[redacted] [redacted]

04 OCT 90 (THU): (U) ~~(S/NF)~~ Provided with an open source document showing cooperation between Expal of Spain (Madrid) and U.S. Honeywell Defense Systems Group, Minnetonka, Minnesota. The Alliance Development Corporation is an international consortium composed of 12 companies based in 8 countries. Two of the companies are Expal and Honeywell.

[redacted]

05 OCT 90 (FRI): (U) ~~(S/NF)~~ The News Media (Press, Radio, TV) released stories of variable credibility concerning Iraqi possession of FAE weapons.

(U) ~~(S/NF)~~ Articles in The Los Angeles Times and The Baltimore Sun referenced a letter dated September 28, 1990 to Secretary of Defense Dick Cheney from five Senators asking for an investigation of the size and sophistication of Iraq's supply of fuel air explosives and whether U.S. technology was used in the weapons development.

(U) ~~(S/NF)~~ An advanced copy of the letter was faxed to TSO from William C. Triplett, II, Senior Staff Member, Committee on Foreign Affairs.

08 OCT 90 (MON): (U) ~~(S/NF)~~ Wrote summary "bullets" at the request of Mike Maloof for use in answering the anticipated Congressional inquiry (letter).

09 OCT 90 (TUE): (U) ~~(S/NF)~~ Called William C. Tripplett, LI, and requested all source documents he used in writing the Congressional inquiry (letter). Lt. Vollkommer picked-up the source documents at 1030 hours.

(U) ~~(S/NF)~~ Analysis of source documents revealed the following:

(a) The conclusions, drawn from the government's sentencing memorandum in the Helmy case are logical but erroneous. [redacted]

(b) The link with MBB is flimsy and based primarily on the BBC TV statement plus MBB acknowledgement that "paper studies" (not technology) was passed to Egypt. Documentation has not yet been received from BBC.

(c) The Congressional letter was well

[redacted] [redacted]

[redacted]

[redacted]

crafted and allows much flexibility if referred to TSO for a response.

(U) ~~(S/NF)~~ [redacted] to sort out fact from fiction in the Congressional working papers.

10 OCT 90 (WED): (U) ~~(S/NF)~~ Developed a graphite chronology for the spread of FAE technology and weapons for the period 1962-1990.

11 OCT 90 (THU): (U) ~~(S/NF)~~ Follow-up with LtCol Ken Garofalo as a routing of a Congressional letter (dated Sept 28, 1990) from Senate Committee on Foreign Relations. Jim Swanson received a call back which indicated that the Congressional letter had inadvertently been sent to another DoD element for answering. However, LtCol Garofalo will attempt to have it routed to TSO.

12 OCT 90 (FRI): [redacted] Honeywell names provided to him. A status report is due back to me on 17 Oct 90.

(U) ~~(S/NF)~~ A brief on FAE using unclassified sources was developed for presentation on Saturday, 13 Oct 90 to OSDTT 0166.

13 OCT 90 (SAT): (U) ~~(S/NF)~~ Presented unclassified brief to OSDTT 0166 on FAE along with Mike Maloof.

15 OCT 90 (MON): (U) ~~(S/NF)~~ Developed and wrote a formal chronology on significant actions taken by me on the FAE issue.

16 OCT 90 (TUE): [redacted]

(U) ~~(S/NF)~~ I requested that he immediately send the messages to me by secure fax. He indicates that they were in his "bosses" office and he would recover them as quickly as possible.

(U) ~~(S/NF)~~ Invited by Nancy Hindman, Munition Control, to a meeting with [redacted] on 18 OCT 90 at 0930 AM. Subject is [redacted] used on Israeli [redacted]

Received fax information from LtCol Atkinson.

[redacted]

[redacted]

following:

[redacted]

17 OCT 90 (WED): Called [redacted] and set-up meeting for Monday, 22 Oct 90 at DIAC.

Received open source information from Chile and Foreign Broadcast Information Service confirming the link between Expal of Spain and Cardoen of Chile for exchange of technical information, testing, and production of FAE weapons.

Drafted interrim response on Congressional (28 Sept 90) letter.

18 OCT 90 (THU): [redacted]

"Wordsmithed" a 2nd draft on the 28 Sept 90 Congressional letter.

[redacted]

Meet with [redacted] for purpose of acquiring information from AF on their information systems.

19 OCT 90 (FRI): Provided LtCol Ken Garofalo with 2nd Draft of FAE Congressional.

Reviewed "El Tiempo" [redacted] on FAE Congressional Response and for meeting on [redacted] Monday, 22 OCT 90 at 1000 in the DIAC. [redacted]

[redacted] He will be in DC on 23-28 October 90... Would like to meet with Mike Maloof, Pat Duecy and Jim Huff. [redacted]

22 OCT 90 (MON): Handcarried the TSO tasking memo of 19 OCT 90 to [redacted] Meet with [redacted] to explain classified aspect of the memo ... Invited them to meet with me at TSO, Tuesday (10/23/90) at 1030.

A decision was made by both LtCol Ken Garofalo and Mr. Frank Bray that our (TSO) response to the Congressional inquiry letter of September 28, 1990 would be "toned down" and "no countries should be identified as supplying FAE weapons or technology to Iraq." Mr. Bray stated that he wanted to make our response "very generic" and that it might take 3 months to finalize a response through all of the "chops." Mr. Maloof was informed of their decision.

[redacted] He is attempting to acquire an original copy of "El Tiempo", 22 OCT 90.

23 OCT 90 (TUE): Received from USDAO Madrid a faxed copy of 22 Oct 90 "El Tiempo" article on FAE.

[redacted]

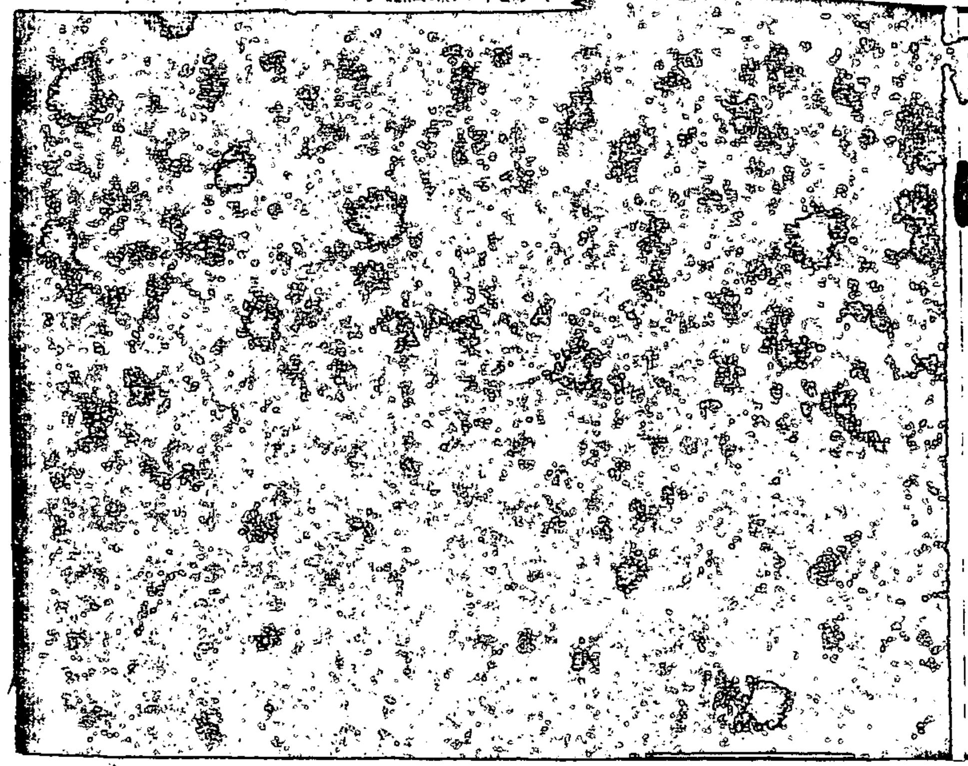
CPT Don Landing made arrangements to have the "EL Tiempo" article translated by FBIS.

[redacted]

[redacted]

[redacted]

24 Oct 90 (WED): [redacted]



24 OCT 90 (THU):

26 OCT 90 (FRI): Developed first draft of FAE slide briefs.

[redacted]

[redacted]

Meet with Congressman Ron Marlenee, LT "Fritz" Vollkommer, and Maj Edward Paterson (Royal Australian Infantry). Provided Congressman Marlenee with an unclassified video copy of the "Front Line" special "The Arming of Iraq" dated 09/11/90.

[redacted]

26 OCT 90 (FRI): Developed first draft of FAE slide-briefs.

[redacted]

Meet with Congressman Ron Marlenee, LT "Fritz" Vollkommer, and Maj Edward Paterson (Royal Australian Infantry). Provided Congressman Marlenee with an unclassified video copy of the "Front Line" special "The Arming of Iraq" dated 09/11/90.

29 OCT 90 (MON): [redacted]

[redacted]

Called by CAPT Jack Garnish (301-985-2787) and asked to coordinate message to Dallas on loss of four (4) billets.

30 OCT 90 (TUE): [redacted]

Went to NAF Andrews and meet LT(JG) [redacted]

Cole concerning the problem in passing of our clearances to DTSA/TSO. I will call him tomorrow and give a status report before he calls LT Henderson (Navy/SSO).

[redacted] Because of an uncleared person in the spaces the conversation had to be terminated. However, I asked [redacted] to provide me with a writing synopsis by COB 31 OCT 90.

[redacted]

31 OCT 90 (THU): Called LT J. W. Cole at RIPO's office TEL (301) 981-5832 for follow-up on passing of clearances for Navy personnel recalled to active duty. LT Richardson (Navy/SSO) (301) 763-3584 apparently sent "info copies" to SSO/DIA instead of "action copy." I subsequently spoke with CDR B. V. Morton (RIPO-19) and advised that if no satisfaction was derived today that I should call LT Richardson's boss, CAPT Pelenski (301) 763-3582.

Received fax from [redacted] on the "Honeywell connection" no significant information was contained in the fax that was not already known to us.

[redacted]

[redacted]

Follow-up with TSGT Aumada, TSO on status of clearances for naval personnel. Tomorrow (1NOV90) the following personnel are to report to Room 5B660, The Pentagon at 1000 hours with copy of orders and ID card.

CAPT J. Huff
CDR C. Campbell
CDR H. Culley
LT R. Potdsnak
IS8 R. Hoobler

1 NOV 90 (THU): Spent morning at Pentagon having clearances passed for following personnel:

CAPT J. Huff
CDR C. Campbell
CDR H. Culley
LT R. Potdsnak
IS8 R. Hoobler

Contact person Petty Officer Dalton TEL #695-7522. DIA badges were delayed because of an administrative "SNAFU".

[redacted]

Briefed [redacted] on status of clearances, and asked that he call RIPO on follow-up for [redacted]

[redacted] There were no questions answered and the information was known to us 3 weeks previously.

Faxed to CDR B.V. Morton (RIDO-19) the 31 OCT 90 "Rudman message" that was sent to CAPT Jim Goldsmith COMNRVRESFOR, New Orleans concerning the withdrawal of 4 billets from NR OSDT 0166.

Called by [redacted] ssue. He will send a summary update by FAX on 5 Nov 90.

2 NOV 90 (FRI): [redacted]

[redacted]

Called by [redacted] and arranged a meeting for 1300 hours.

Received a call from SGT Twillie, SSO/DIA concerning "perm cert" clearance for Navy Desert Shield personnel. SGT Twillie indicated she would put the "original five" into the computer and I agreed we would not need level 6 DIA badges. Called Maj J. Nunez, USA, DIA (703) 695-1608 for author TEL number for IIR 1 517 003791, DTG 232200Z 90. I was informed by Ms. Yvette Woulgy, Senior Analyst, that Major Nunez was transferred to the Joint Intelligence Command (JIC) and replaced by Bruce Davidson who would provide me the name and number on Monday 11/5/90.

2 NOV 90 (FRI): [redacted]

3 NOV 90 (SAT): [redacted]

5 NOV 90 (MON): [redacted]

CAPT Bill Williamson. LT(JG) Bill Hunt is doing a question/answer evaluation of their response.

Meet with Mike Maloof and LCDR Paul Hollich and resolved operational issues concerning the use of talented reserve officers on 14-17 day annual training. In a case specific issue, Mike indicated that CAPT Bill Williamson will be used on the [redacted]

I indicated that we are planning a "dining-out" or "unit dinner party" in Feb, 1991 and the entire staff were invited as members.

Mike and Paul stated that when "the crisis" is over they wanted to go in for a unit meritorious award.

I mentioned that LT Diane Douglas had an idea that I would like for them to hear directly from her.

I also discussed having the unit do "open source" searches between drills. The idea was well received.

Also, I indicated that we are developing a unit matrix on skills, country expertise, and clearances. A smooth copy should be ready this week.

7 NOV 90 (WED): [redacted]

8 NOV 90 (THU): [redacted]

Meet with Ken Shelley, DTSA, (Munitions) Tel 693-1165 and he provided technical information on the U.S. fuse 732. [redacted]

[redacted]

13 NOV 90 (TUE): (A) Meet with Ken Shelly, DTSA (Munitions) Tel (703) 693-1165 concerning transfer of U.S. Government proximity fuse 732 technology [redacted]

[redacted]

[redacted]

[redacted]

19 NOV 90 (MON): [redacted]

(C) Meet with Don De Fago Strategic Investigations Division, Chief of Munitions Branch, (Customs) 1301 Constitution AVE, Wash DC (202) 343-9694, FAX (202) 377-9240.

[redacted]

(3) Customs currently has provided DoD with no information on this case.

(4) TSO will develop a summary of known facts and provide same to DoD and DIA.

[redacted]

20 NOV 90 (TUE): (A) Meet with following DIA personnel at the DIAC:

[redacted]

[redacted]

21 NOV 90 (WED): [redacted] He is to provide us a copy of his briefing slides on Friday, 23 NOV 90.

Leave control numbers were acqired and leave requests signed-off for five members of recall detachment for Thanksgiving.

26 NOV 90 (MON): [redacted]

SECRET

[redacted]

27 NOV 90 (TUE) [redacted]

Met with Meade Fields, U.S. Customs Agent, and DOD Liaison Officer (202) 566-2950.

[redacted]

28 NOV 90 (WED) (A)

[redacted]

SECRET

SECRET NOFORN

M0120;
BM21;
M8513;
M85R13;
AB103;
AB108.

U (S) Met with [redacted] to follow-up on questions FAXED to [redacted] by LT Jim Swanson on 09 NOV 90.

29 NOV 90 (THU) Met with Mike Maloof, LCDR Paul Hollick, LCDR-S Diane Douglas, CAPT Don Landing (USAF), Mr. Larry Fitzgerald and Neville Dennis on <u>necessary changes to the current Data Base and Technical Support by DTSA.</u> A time table was established and a deadline of 15 JAN 91 was set. See attached memo of 29 NOV 90.

SECRET NOFORN

RELEASABLE #8

OFFICE OF THE UNDER SECRETARY OF DEFENSE

WASHINGTON, D.C. 20301-2000

NOV 20 1990

POLICY

Honorable Connie Mack
U.S. Senate
Washington, D.C. 20510-0904

Dear Senator Mack:

Secretary Cheney has asked me to respond to your letter of 28 September 1990, asking the Defense Technology Security Administration to determine Iraq's capability to deliver Fuel Air Explosives (FAEs) against the military forces of the United States or its allies in the Persian Gulf. You also asked what FAE technology Iraq has obtained, how it was obtained, and the original source of the technology.

Iraq clearly has the capability to use FAE weapons against U.S. forces in the Persian Gulf. Such weapons would most likely be delivered by fighter-bomber aircraft using gravity FAE bombs. However, Iraq also has the capability to deliver FAE weapons from helicopters.

In May 1989 at the Baghdad Military Airshow, Iraq displayed several FAE bombs. These weapons contained components that had either been provided by foreign sources or had been copied from foreign weapons. One bomb, for example, had been fitted with Soviet-made fuzes.

Generally, however, the technology required to produce FAE munitions is uncomplicated and readily available to knowledgeable weapon manufacturers. There are no specific technologies which are unique to FAE weapons.

The chemicals used in the production of FAEs are standard non-military processing chemicals which are easily obtained on the world market. The embargo of precursor chemicals and other components will probably slow the Iraqi production of FAE weapons. However, the Iraqis are currently constructing a petrochemical complex that will enable them to indigenously produce most FAE ingredients.

Of the technologies required to produce an FAE, the fuze is the most difficult and it is in this area that foreign assistance has given Iraq's FAE program its greatest boost. One Latin American firm has provided Iraq with a turnkey military fuze factory near Baghdad which may be producing the fuzes necessary for FAE weapons.

We are looking into the allegations cited in your letter, which were made by the British Broadcasting Service, that the German firm, Messerschmitt-Boelkow-Blohm (MBB), provided another country with FAE technological assistance that eventually may have gone to Iraq. The firm itself admits that FAE technology was transferred. The question remains as to what was transferred and if it was transferred in violation of the Missile Technology Control Regime.

We also are investigating whether U.S. FAE technology has been transferred or diverted by U.S. companies or citizens to Iraq, either directly or through intermediary foreign companies. When these investigations have been completed, we will inform you of the findings.

Thank you for your interest in this matter. If you have any further questions, please do not hesitate to let me know.

Sincerely,

William Rudman

William N. Rudman
Deputy Under Secretary
Trade Security Policy

ORIGINALS SENT TO:

SEN. HELMS
HEINZ
GLENN
DIXON

DISTRIBUTION:
Original + 1 cy for addressee
OSD/CCD - 1 cy
ASD(LA) - 1 cy
DSAA CONG REL - 1 cy
CMD - 1 cy
DUSD/TSP - 1 cy - held
ADUSD/TSP - 1 cy - held
NON-PROLIF - 1 cy
USD(A) - 1 cy
JCS - 1 cy
OASD(PA) (DFOISR) - 1 cy
DTSA/TSO - 1 cy - held
DTSA/IGA - 3 cys - held

Prepared by KGAROFALO:nmb:11-14-90:DTSA/IGA:400 A/N Dr.:X37110

United States Senate

COMMITTEE ON FOREIGN RELATIONS
WASHINGTON, DC 20510-6225

September 28, 1990

The Honorable Richard Cheney
Secretary of Defense
The Pentagon
Washington, D. C. 20301

Dear Dick:

On September 3, 1990, the British Broadcasting Corporation (BBC) charged that American and allied forces in the Persian Gulf may be at risk from Iraqi ballistic missiles armed with Fuel Air Explosive (FAE) warheads. Weapons specialists agree that FAE's are particularly effective against soft targets such as personnel in the open and air bases.

Of particular concern is the BBC's allegation that Iraq obtained the technology to produce FAE's from Messerschmitt-Boelkow-Blohm (MBB), Germany's largest aerospace firm and a major partner of the Airbus Consortium. If such a transfer took place, it would have occurred during the course of the Egyptian-Iraqi Condor II ballistic missile project to which MBB was a major contractor. In a letter of August 28, 1990 addressed to the BBC from Mr. W. Vogler, Head of Public Relations, the firm confirms that FAE technology "was transferred to the client".

In 1989 Mr. Abdelkader Helmy, an American of Egyptian origin was arrested and later convicted of attempting to illegally export US-origin ballistic missile technology to Egypt. Information developed during this case revealed that Mr. Helmy and the others convicted with him were illegal purchasing agents for the Condor II missile program. Pages three to five of the Government's Sentencing Memorandum in the Helmy case reveal that Mr. Helmy was tasked by the Condor II managers with obtaining US-origin FAE technology for "a ballistic missile project" (page 5 of the Memorandum). In fact, in September 1985 Mr. Helmy tried to obtain a license to export FAE technology but was refused a Munitions License by the Department of State.

The chain from Mr. Helmy to Iraq by way of Egypt, MBB and the Condor II program strongly suggests that Iraq has illegally obtained US-origin FAE technology. Given the clear danger to American and allied military personnel from Iraqi ballistic missiles armed with FAE warheads and the fact that MBB is a contractor to sensitive U.S. defense projects, it is vital that an immediate and full investigation be made of what technology was transferred to Iraq and by whom.

Therefore, please direct the Defense Technology Security Agency (DTSA) and such other agencies of the Federal Government as you seem appropriate, to determine Iraq's capability to deliver Fuel Air Explosives on the military forces of the United States or its allies in the region. Such an investigation should focus on what FAE technology Iraq has obtained, how it was obtained and the source of the technology. We would anticipate that, should the investigation determine that any U. S. or foreign firms are culpable, contract debarment procedures would be initiated immediately.

Thank you for your attention to this matter.

Sincerely,

Alan J. Dixon

Jesse Helms

Connie Mack

John Heinz

John Glenn

#9

RESPONSE TO CONGRESSIONAL INQUIRY

30 OCT 90

Fuel-Air Explosive (FAE) threat to U.S./Allied forces.

- The best available information indicates that Iraq has the capability to effectively use FAE weapons against U.S./Multinational forces. Contrary to press reporting, FAE weapons are not "super bombs". However, they are among the most lethal devices in the conventional armory. FAE weapons are several times more destructive than similar conventional military explosives of the same size. They are unique in that they create extremely high blast overpressures without the fragmentation effects of traditional explosives and are especially effective against personnel and non-hardened targets.

- The primary delivery vehicles for Iraqi FAE weapons are fighter-bomber aircraft. These aircraft would use gravity FAE bombs. There is some evidence of Iraqi capability to launch FAE weapons from helicopters and as warheads on missiles. The use of FAE warheads on tactical battlefield missiles has not been confirmed.

- The Iraqis have claimed that they used FAEs effectively in the Iran/Iraq war. However, there is little information concerning the operational use of Iraqi FAEs during the Iran/Iraq war or evidence of their use in recent Iraqi ground/air training operations.

Iraqi FAE production technology.

- The technology required to produce FAE munitions is largely uncomplicated and is readily available to knowledgeable weaponeers. There are no specific technologies or components which are unique to FAE weapons. The fuze mechanism for the bomb is the most technically difficult item, however Cardoen Industries of Chile has assisted Iraq in the construction a turnkey factory near Baghdad for military fuzes, including FAE fuzes.

- The chemicals used in the production of FAEs are standard non-military processing chemicals readily available on the world market. The embargo of precursor chemicals and other components will probably slow the Iraqis in producing FAE weapons. However, the Iraqis are constructing a petrochemical complex that will enable them to indigenously produce most FAE ingredients.

Foreign involvement in FAE technology transfer to Iraq.

- The media has, at various times, involved German, Spanish and Chilean enterprises in the sale of FAE technology and/or weapons to Iraq. Contrary to British press allegations, there is no conclusive evidence that Messerscmitt-Boelkow-Blohm (MBB), a German firm, provided FAE components, designs or other technical assistance to Iraq that would have enabled them to develop an operational FAE weapon. MBB admitted openly that they provided FAE "guided missile" technical analyses and studies to Egypt. Past Egyptian and Iraqi cooperation in missile programs leave open the possibility that FAE information was transmitted to Iraq. However, incontrovertible evidence is currently lacking.

- In May 1989, at a Baghdad military show, the Iraqis displayed several FAE bombs. One of these bombs had original or copied FAE components from EXPAL, a Spanish arms company. The bombs were also fitted with Soviet-made fuzes. It is unknown how these fuzes were obtained.

U.S. involvement in FAE technology transfer to Iraq.

- There is an ongoing investigation to determine whether U.S. FAE technology was transferred or diverted by U.S. companies or citizens to an intermediate country and subsequently to Iraq.

data to IFAT. As yet, we do not know details of the data provided. If Honeywell provided missile inertial guidance to IFAT, that would mean Iraq may well have a capability which we thought it still lacked for its missiles.

- Separately, my office over the past few weeks has been in contact with Honeywell to obtain:
  a) Information of other data Honeywell supplied to IFAT and to Keith Smith.
  b) All names of Honeywell employees who worked under Ward Weaton on FAE's and cluster bombs. [redacted]

transfer to FBI

- In this connection, we now believe that Honeywell provided some of the FAE technology that made its way to Iraq. Iraq in turn hired Cardoen of Chile and Expal of Spain to make the FAE's, based on the Honeywell data. We continue to believe that technical weapons assistance came from U.S. technicians. This is where ISC may have brokered technical experts to go to Chile to assist in this effort.

b(7

- Early on in our probe which led to Honeywell, the company initially denied any involvement in this work. Ironically, Honeywell now has sold off the Aerospace and Defense portion to a separate company called Alliant in September, 1990.

Recommendation: Accept the visitors. Be only in a listening mode. Ask to be kept fully apprised of its internal probe. Also ask for Honeywell to look into any assistance Honeywell employees may have given to Cardoen.

Michael Maloof

Michael Maloof
Director
Technology Security Operations

b(5), b(4) #10

THE OFFICE OF
THE UNDER SECRETARY OF DEFENSE

WASHINGTON, D. C. 20301-2000

DEC 7 1990

POLICY

MEMORANDUM FOR THE DEPUTY UNDER SECRETARY OF DEFENSE, TRADE SECURITY POLICY

SUBJECT: Honeywell (U) -- INFORMATION MEMORANDUM --

Honeywell wants to meet with you about recent published and broadcast accounts of its alleged part in Iraqi development of fuel air explosives (FAE's). The company has come to DTSA due to our review of how FAE technology was acquired by Iraq. As you will recall, our involvement in this issue was in response to a Congressional inquiry.

We were aware of Honeywell's involvement in U.S. FAE research earlier on but only alluded to possible U.S. technology in the interim response to five U.S. Senators. Our investigation of the FAE issue continues.

The company may want to "fish around" to find out what we know. In response to an NBC broadcast on the subject last week, Honeywell has launched its own internal probe. Here is what we know:

- Honeywell in 1984 passed two generic documents on FAE's to a Keith Smith of IFAT in the UK, a parent of a group comprised of Egypt, MBB (Germany), and Argentina involved in the development of the Condor missile. Egypt was thought to be the likely recipient of the technology. But at that time, Egypt shared Condor missile development with Iraq. In effect, FAE's were to be the warhead for Condor. Only Iraq continued Condor development, using it as a basis for its later generation missiles.

- Ward Weaton of Honeywell, then Vice President for Aerospace and Defense, ordered Honeywell to provide the reports to IFAT. He is now retired. IFAT paid considerable amounts of money for the reports at a time when Honeywell needed the cash. U.S. interest in FAE weapons waned in the early 1982-85 time frame. Smith reportedly had access to a billion dollar account underwritten by Saudi Arabia.

- The FAE reports are generic; our technical people have reviewed them. Nothing in them is licensable. However, they make reference to four classified reports. We are conducting a security check of the documents now.

- Not yet published is a tip I received that Honeywell also provided inertial guidance and ring laser gyro data to IFAT. As yet, we do not know details of the

Release

b(5)

#11

CONVERSATION RECORD

TIME 1400

DATE 11 DEC 90

TYPE

☐ VISIT ☒ CONFERENCE ☐ TELEPHONE ☐ INCOMING ☐ OUTGOING

ROUTING

NAME/SYMBOL	INT

Location of Visit/Conference:

NAME OF PERSON(S) CONTACTED OR IN CONTACT WITH YOU

ORGANIZATION (Office, dept., bureau, etc.) Honeywell

TELEPHONE NO: see attached

SUBJECT

Meeting with 3 Honeywell Representatives, Michael R. Bonsignor, Ronald H. ~~Burns~~ Burnhart and Dallas D. Burns.

SUMMARY

Following points were discussed and agreed upon during the meeting:

1. Honeywell agreed to cooperate in every possible way to help determine what FAE technology was transferred from their UK Division to IFAT in Switzerland & They stated that they would also supply TSO with copies of all correspondence and reports that were involved;

2. Capt Huff asked Ronald H Barnhart to make sure that ~~we~~ TSO had an entree to Alliant and that Alliant, also, would cooperate with the investigation. He agreed with this request.

The meeting was both open and positive. (OVER)

ACTION REQUIRED

NAME OF PERSON DOCUMENTING CONVERSATION

Capt. JAMES A. Huff

SIGNATURE [signature]

DATE 12 DEC 90

ACTION TAKEN

SIGNATURE

TITLE

DATE

50271-101
U.S. GPO: 1987—181-247/60121

CONVERSATION RECORD

OPTIONAL FORM 271 (12-76)
DEPARTMENT OF DEFENSE

CONVERSATION RECORD

TIME: 1145

DATE: 11 DEC 90

TYPE: ☐ VISIT ☐ CONFERENCE ☒ TELEPHONE ☐ INCOMING ☐ OUTGOING

ROUTING: NAME/SYMBOL | INT

Location of Visit/Conference:

NAME OF PERSON(S) CONTACTED OR IN CONTACT WITH YOU: Mr. Pete Romatowski

ORGANIZATION (Office, dept., bureau, etc.): Crowell + Moring DC Law Firm

TELEPHONE NO: (202) 624-2745

SUBJECT

Mr. Romatowski represents Alliant, which is a spin-off of Honeywell (Sep 1990). He is an attorney with the DC Law Firm Crowell and Moring.

SUMMARY

LT Vollkommer returned Mr. Romatowski's phone call. Mr. Romatowski informed LT Vollkommer the he and his firm represent Alliant. He asked LT Vollkommer what information LT Vollkommer wanted from Alliant as he (Romatowski) had been informed by Alliant that LT Vollkommer had contacted them. LT Vollkommer informed Mr. Romatowski that he (Vollkommer) could not answer ~~that~~ what information had been or will be requested from Alliant as the file was taken to a meeting by LT Vollkommer's Captain. Mr. Romatowski asked who it was that LT Vollkommer worked for and was informed DTSA and that DTSA delt with Technology Transfer issu (Romatowski asked what DTSA was involved with.) LT Vollkommer informed Mr. Romatowski that he (Vollkommer) would call him (Romatowski) back either in the afterno (over)

ACTION REQUIRED

Return Mr. Romatowski's call if Cpt. Huff so chooses.

NAME OF PERSON DOCUMENTING CONVERSATION: LT. Frederick C. Vollkommer

SIGNATURE: Frederick C. Vollkommer

DATE: 12 DEC 90

ACTION TAKEN

SIGNATURE | TITLE | DATE

CONVERSATION RECORD

TIME: 1120
DATE: 12 DEC 90

TYPE: ☐ VISIT ☐ CONFERENCE ☒ TELEPHONE
☒ INCOMING
☐ OUTGOING

Location of Visit/Conference:

NAME OF PERSON(S) CONTACTED OR IN CONTACT WITH YOU	ORGANIZATION (Office, dept., bureau, etc.)	TELEPHONE NO:
RONALD BARNHART	VICE PRESIDENT HONEYWELL, DC	(703) 827-3566

ROUTING

NAME/SYMBOL	INT

SUBJECT: CALL FROM MR. ROMATOWSKI, ATTORNEY FOR ALLIANT.

SUMMARY

MR BARNHART ATTENDED THE MEETING OF HONEYWELL AND DTSA/TSO OFFICIALS ON 11DEC90.

HE INDICATED THAT HE WOULD CALL MR. ROMATOWSKI AND INSTRUCT HIM TO COOPERATE FULLY WITH TSO STAFF. (ALLIANT IS A "SPIN-OFF" COMPANY FROM HONEYWELL)

HE ALSO STATED THAT HE FELT THE MEETING OF 11DEC90 WAS EXTREMELY USEFUL AND PRODUCTIVE.

ACTION REQUIRED: MR BARNHART IS TO CALL ME AFTER SPEAKING WITH ROMATOWSKI AND ALLIANT SENIOR OFFICIALS

NAME OF PERSON DOCUMENTING CONVERSATION	SIGNATURE	DATE
JAMES A. HUFF	[signature]	12 DEC 90

ACTION TAKEN

SIGNATURE	TITLE	DATE

#12

CONVERSATION RECORD

TIME 1245 | DATE 22 October 92

TYPE ☐ VISIT ☐ CONFERENCE ☒ TELEPHONE ☐ INCOMING ☐ OUTGOING

Location of Visit/Conference:

ROUTING	
NAME/SYMBOL	INT

NAME OF PERSON(S) CONTACTED OR IN CONTACT WITH YOU	ORGANIZATION (Office, dept., bureau, etc.)	TELEPHONE NO:
TOBY DARCY	OGC	77215

SUBJECT
FOIA

SUMMARY

1. Internal attorney-client product...
May be releasable

2. HONEYWell internal documents...

3. Studies

ACTION REQUIRED

NAME OF PERSON DOCUMENTING CONVERSATION	SIGNATURE	DATE

ACTION TAKEN

SIGNATURE	TITLE	DATE

612

473-4546

Ward Wheaton, VP, Aerospace & Defence, (612)
Retired (Honeywell) (Minnesota)
everyone in Aero - Defence for wked for him.

Keith Smith → IFAT → marketing type.
don't know locale now

Garrith Thornton ⇒ don't know name.
011 - 44-344-424555 ?

M. C. Newman -
M. R. Webb -
M. J. Dix -
Brian Gowers -

NOT in book.

↳ Marketing manager at UK, might have left Honeywell prior to 1989. Got better offer.

L. P. Lavoie Defence System Division

APGM PROGRAM TEAM LIST

Program Management			
Director of Programs	~~Hanson, WR (Dick)~~	~~931-4374~~	~~MN38-4300~~
APGM Program Manager	Svärd, T (Trygve)	931-4443	MN38-1200
Development Engineering			
Mechanical Design	Aliaghai, H (Hossein)	939-2087	MN50-2450
Embedded Software	Arko, C. (Craig)	931-4441	MN38-2300
Lead Software Engineer	- Belfry, DP (Dave)	931-4342	MN38-3100
Aero Design	* Bell, DR (Don)	931-4583	MN38-3300
Engineering Sevices	Bennett, KE (Karl)	931-4154	MN61-0000
Lead Aero Engineer	- Cvetnic, J (John)	931-4827	MN38-3300
Mechanical Design	Erickson, M. (Mitch)	931-4252	MN38-3300
Warhead Engineering	Herman, P (Paul)	536-4816	MN48-3700
Software Engineer	Hoffman, J. (John)	931-4441	MN38-2300
Director	Paulson, D (Dave)	931-4062	MN38-5140
Warhead Engineering	* Houlton, JL (Joel)	536-4510	MN48-3700
Lead Mechanical Design	- Leone, J. (John)	931-4404	MN38-3300
Integration & Test	* Makela, W (Weldon, 'Mac')	931-4246	MN61-0000
Development Engineer	Moy, M. (Mike)	931-4734	MN61-0000
Software Engineer	Moy, P. (Phillip)	931-4987	MN38-2300
Development Engineer	Neher, N. (Norm)	931-4892	MN38-3300
Warhead Engineer	- Nelson, CA (Carl)	536-4499	MN48-3700
Lead Test & Evaluation	- Steffl, L (Leo)	931-4560	MN61-0000
Guided Projectiles	* Stewart, DG (Douglas)	939-2149	MN50-2450
Software Engineer	* Weinstein, D. (Dennis)	931-4011	MN38-2300
Embedded Software	* Wicklund, TL (Tom)	931-4896	MN38-2300
Systems Engineering			
System Technology Staff	Alford, RL (Bob)	931-4041	MN38-2100
Systems Engineer	Blazei, M. (Mark)	939-2384	MN50-2600
Systems Engineer	Bohlman, G. (Gary)	939-2505	MN50-4600
Project Support	- Bohn, GL (Gerald)	931-4290	MN38-2300
Director	Boyle, JJ (John)	931-4230	MN38-5130
Systems Integration	Eidenschink, T. (Tracee)	931-4751	MN38-1400
Sensor Analysis, *Ulm, Germany office*	- Ener, O (Oran)	011-49-731-37421; 37422; or 37423	
Mission Analysis	* Forrest, TR (Terry)	931-4959	MN38-2500
System Analysis	Gerber, RB (Rick)	939-2327	MN50-2450
System Management Section Head	Grauze, DL (Dal)	931-4325	MN38-2500
System Technology Staff	Josselson, RH (Bob)	931-4156	MN38-2500
Configuration Management	Kardon, S (Steve)	931-4510	MN38-2500
Product Effectiveness	* Luedtke, HW (Howard)	931-4328	MN38-2300
System Technology Staff	- Mueller, CE (Conrad)	931-4747	MN38-2500
Design Assurance	- Novak, BJ (Brian)	931-4355	MN38-2300
System Integration	- Nutzmann, D (Don)	931-4315	MN38-2100
System Analysis	* O'Connor, M (Michael)	931-4282	MN38-2500
Mission Analysis	- Oleckl, J (Jim)	931-4464	MN38-2500
Technical Director	Storsved, D (Doug)	931-4004	MN38-1200
System Analysis	Uppal, SY (Sohail)	931-4314	MN38-2500
Mission Analysis	Verzal, P (Patty)	931-4078	MN38-2500
Sensor Analysis	Wiersma, DJ (Dan)	939-2508	MN50-2450
Configuration Management	* Yoong-Lee, V (Virginia)	931-4349	MN38-2300
Quality			
Lead Quality Engineer	- Erickson, D (Duane)	939-2112	MN50-2600
Quality	* Pavlisich, E (Ernie)	939-7557	MN38-1150
Director	Sixel, DE (Doug)	931-4010	MN38-5120

KEY: * CAMs
- Technical Lead

SRC

Management	Farvog, F (Fred)	782-7704	MN65-2600
Engineering	Johnson, DC (Dean)	782-7727	MN65-2600
Contracts	Prochniak, W (Wayne)	782-7652	MN65-2410
Engineering Mgr./Program Mgr.	Touchberry, A (Alan)	782-7733	MN65-2600
Marketing	Waage, M (Mike)	782-7708	MN65-2600

Business Support

Trygve Svärd's Temp. Secretary	Albrecht, C. (Catherine)	931-4945	MN38-1200
Program Control/Cost	* Aschenbeck, L (Lisa)	931-4996	MN38-4000
Marketing	Paryz, LE (Larry)	931-7080	MN38-4200
Interdivisional Specialist	Benson, D (Dave)	939-2078	MN50-2300
Legal Counsel	Bryant, B (Bev)	931-7010	MN04-1342
DSG Finance	Gray, B (Betty)	931-4968	MN38-5500
International Export Control Officer	Hirsch, S (Steve)	536-4549	MN48-3900
Program Control/Schedule	Leonard, L (Lynda)	931-4584	MN38-4000
Contracts	Linnell, R (Becky)	931-7572	MN38-4200
Scheduler	Peterson, M (Mary)	931-4976	MN38-4000
Finance Manager	Picek, J (John)	931-4063	MN38-5105
Administration	Porter, MR (Mitch)	931-4490	MN38-
Action Item Management	Monicatti, C. (Chris)	931-4956	MN38-1200
Contract Manager (Export Control Mgr)	Rockney, RJ (Robin)	931-4786	MN38-4200
Administration (Lead)	Stoltzman, L (Lynn)	931-4465	MN38-1200
Administration	Wieker, T (Teresa)	931-7065	MN38-1200
	Teresa's number at Edina	939-2355	

ADCO

Systems Engineering	Hilal, M (Marc)	932-0418	MN04-2250
Deputy Technical PM	* Jaeneke, C (Christian)	932-0401	MN04-2250
Business Management	Lanz, DE (Del)	932-0426	MN04-2250
Test Engineering	Lee, DL (Duane)	932-0415	MN04-2250
General Manager	Massey, PA (Pete)	932-0400	MN04-2250
Engineering	* Midrouillet, D (Daniel)	932-0417	MN04-2250
Deputy Business PM	Neale, MG (Gordy)	932-0402	MN04-2250
Administrative Manager	Odle, R (Dick)	932-0424	MN04-2250
Systems Engineering	Phelps, RK (Ken)	932-0412	MN04-2250
Subcontracts	Remski, R (Bob)	932-0410	MN04-2250
System Engineer	* Reumers, J (Jean)	932-0413	MN04-2250
Airframe Systems	Rupert, JG (John)	932-0414	MN04-2250
Controller	Schmitt, L (Larry)	932-0436	MN04-2250
Contract Representative	Schnorbach, P (Peter)	932-0411	MN04-2250
Marketing	Steiner, PD (Fred)	931-4790	MN04-1313
Marketing	Umholtz, VF (Vern)	932-0420	MN04-2250
Subcontract Manager	* Voccia, G (Giuseppe)	932-0409	MN04-2250

Temporary Secretaries at ADCO:

GM Secretary	Nordquist, Gloria	932-0404	MN04-2250
	Erickson, Judy	932-0406	MN04-2250
	Teski, Meredith	932-0405	MN04-2250

Fax Numbers	ADCO	932-0440	(verify 932-0406)
	Edina	939-2480	(Copy Center, verify 939-2479)
		939-2954	(Procurement)
	Northland	536-8192	(Copy Center, verify 536-4164)
	Shady Oak	931-4110	(Copy Center, verify 931-4059)
		931-4311	(Marketing)
	Bren Road	931-4233	

KEY: * CAMs
- Technical Lead

Revised 10 August 1990
Contact Catharine Albrecht at 931-4945 for changes to this list.

OOR FAX (703) 614-6392

Martha Cooper

① All Inertia Guidance and everything else that Keith Smith got from Honeywell. Sent me copies of everything.

② List of everyone that worked for Ward Wheaton. (Already asked for this). <about 20,000 people>
Call Department Heads / FAE's + Cluster Bombs

05DEC90 Try to get back to me today. #2 above has to come from Honeywell & Personnel, they are working on it.

Jenefer Crawford (612) 870-6182 > she is getting info for me.

→ Request in writing ←

Keith Smith
< 1984 FAE, report sending it >
Don't know what else

Jennefer Crawford

Alliant Tech ; Legal Council : for Ward Wheaton's peopl
Chuck De Ericson
(612) 931-6082

What info was shared with other US firms -

Doc #1c

ALLIANT TECHSYSTEMS, INC.
1725 JEFFERSON DAVIS HIGHWAY
CRYSTAL SQUARE TWO, SUITE 901
ARLINGTON, VA 22202
PHONE: (703) 271-4600

TO: ~~Linda Randall~~

694-7753

to Capt Hutt DTSA/TSO

per Nancy Hardin

FROM: MARTHA COOPER

(703) 271-4625

DATE: Nov. 7, 1990

NUMBER OF PAGES 2

4/19/91

MOR

MOR

CALLED JoH... REQUESTED ISC AND H... SUGGESTED MARKE... FROM EACH OTHER

REQUESTED THAT MR. STENGER FAX INFORMATION ON "COMBINED EFFECTS MUNITIONS PROGRAM" TO ME TODAY! THIS QUOTE REFERS TO CLUSTER BOMBS.

[signature]

Honeywell

#14

FAE

Head Bob Mockenhaupt; retired

Current ~~P~~ Denny Longren
VP Ordanance Systems
(612) 939-2400

Direct Marketing Larry Blagdon
(612) 536-4393

Program (for Future) Paul Newell
(612) 939-2445

Marketing Mgr ~~Bern~~ Vern Umholtz
(612) 932-0420

lost ~~CAT FAE~~ CAT FAE, are doing nothing currently in FAE.

Who was WARD WEATON? — Who worked for him?
Ask Honeywell to supply the Repts. to IFAT given in 1984.
Who wrote the repts?
Who was Keith Smith of IFAT?
" " PARRITH THORNTON of Honeywell?
Who designed FAE'S FOR Honeywell?

IFAT = Institute For Advanced Technologies

Honeywell

Cluster Bombs

Group VP — Denny Longren
(612) 939-2400

Dir Marketing — Larry Blagdon
(612) 536-4393

Program Director — Veijo Paine
(612) ~~8~~ 639-7136

#15

IGA LOG #: 420 DATE/TIME: 12 /10/90

APPOINTMENT REQUEST

VISIT: __ __ INTERVIEW: __ __ MEETING: _X_ __ SPEECH: __ __ OTHER: __ __

DUSD/TSP: __ __ ADUSD/TSP: _x_ __ DIRECTOR: __ __

Referred by:

Key Person(s)/Title: Mike Bonsignore Exec VP and CEO (International), Burnes (VP-Corporate Solid State Prod), Ron Barnhart (VP) - Gov't Systems Marketing

Organization: Honeywell

Requestor/Telephone: Ron Barnhart (VP-~~Washington~~ Office)

Subject: Honeywell Involvement in Iraq FAE technology transfer.

Date: 11 Dec 90 Time: 1430 Place: SP Conference Room

DTSA Staff to be Present*: Maloof, Menas, Konfala (Richey & Griffin optional)

IGA Comment/ Recommendation: Mr. Rudman has already agreed to meet with Honeywell.

IGA Action Officer: Garofalo

FRONT OFFICE USE

Calendar is clear:__________
Alternate date:__________

MA has seen:__________

DUSD/TSP	ADUSD/TSP
Accept______	Accept______
Decline______	Decline______

Comments: __________

---

cc: All Directors, MA, SA

*IF YOUR DIRECTORATE HAS NOT BEEN INVITED TO ATTEND THIS EVENT AND YOU FEEL YOU SHOULD ATTEND PLEASE NOTIFY IGA, ASAP.

ALL MEETINGS WHICH DUSD/TSP OR ADUSD/TSP ATTEND REQUIRE A PRE-BRIEF.

Management, Products & Facilities

Aerospace & Defense

W. F. WHEATON,
Executive Vice President

Staff: R. H. Barnhart, Vice President Marketing—W. B. Melin, Vice President & Controller—G. E. Peters, Vice President & Staff Executive—L. R. Weisberg, Vice President Research & Engineering.

Avionics Systems Group:
M. A. Sutton, Vice President & Group Executive.

Defensive Electronic Systems:
R. L. Rynearson, Vice President.

Electro-optical systems, infrared sensors, microwave technology. **Headquarters:** Minneapolis, MN. **Manufacturing:** Santa Barbara, CA.

Commercial Aviation Division:
J. R. Dewane, Vice President & General Manager.

Laser inertial reference, navigation and guidance systems, fuel-quantity indicating systems, air-data computers, radar altimeters, pressure-ratio devices and worldwide engineering service centers. **Headquarters and manufacturing:** Minneapolis, MN.

Electro-Optics Division: G. C. Vandevoort, Vice President & General Manager.

Electro-optical systems and components, threat-warning systems, infrared sensors and seekers, mercury cadmium detectors. **Headquarters:** Lexington, MA. **Manufacturing:** Marlboro, Wilmington, and Sudbury, MA.

Military Avionics Division: S. F. Moeschl, Vice President & General Manager.

Laser inertial navigation and guidance systems, flight controls, inertial sensors, communications systems and components, radar altimeters, automatic test equipment, display and sighting systems, aircraft and missile systems and components. **Headquarters:** Minneapolis, MN. **Manufacturing:** Minneapolis, MN—Clearwater, FL.

Space and Strategic Avionics Division:
C. L. Vignali, Vice President & General Manager.

Precision guidance and navigation systems, flight and engine control systems for manned and unmanned spacecraft, electronic components for boosters and missiles. **Headquarters:** Clearwater, FL. **Manufacturing:** Clearwater, FL—Annapolis, MD.

Defense and Marine Systems Group:
R. J. Boyle, Vice President & Group Executive.

Defense Systems Division:
R.R. Mockenhaupt, Vice President & General Manager.

Precision munitions, ammunition, scatterable mines, fuzed and air-delivered weapon systems, fire-control equipment. **Headquarters:** Minneapolis, MN. **Manufacturing:** Minneapolis, MN—Horsham, PA—Joliet, IL.

Marine Systems Division: J. L. Holman, Vice President & General Manager.

Acoustic-sensing and sonar systems, mine-neutralization systems, oceanography equipment, engineering services, vessel positioners. **Headquarters and manufacturing:** Seattle, WA.

Tetra Tech, Inc.: H. Hodara, President.

Remotely controlled marine vehicles, underwater television systems, water-resource management, environmental-impact studies, hazardous-waste-disposal consulting and engineering services for offshore-oil and utility industries, marine construction, deep-sea operations. **Headquarters:** Pasadena, CA. **Manufacturing:** San Diego, CA.

Training and Control Systems Operations: T. G. Warson, Vice President & General Manager.

Training devices and systems, visual systems, Naval combat systems. **Headquarters:** West Covina, CA. **Manufacturing:** West Covina and Azusa, CA.

Underseas Systems Division:
C. O. Larson, Vice President & General Manager.

Torpedoes and underseas systems, components, ceramic components. **Headquarters and manufacturing:** Minneapolis, MN.

Defense Communications and Production Division: A. W. Kelley, Vice President & General Manager.

Military communications equipment. **Headquarters and manufacturing:** Tampa, FL.

Systems and Research Center:
J. S. Dehne, Vice President.

Systems analysis and applied research on systems and products for military and space sectors. **Headquarters:** Minneapolis, MN.

1984 Annual Report

Country: ENGLAND & WALES

Date of Incorporation: 11Sep1989
Accounting Reference Date: 30May
Date of Last Return: 25Sep90
Date of Annual Account: 31May90

This is a LIVE company

Company Type: Private limited with share capital
Account Type: SMALL COMPANY
Nominal Capital (Sterling): 1,000
Issued Capital (Sterling): 2

LAST UPDATE AND TRANSACTION
21Nov90 Annual Return Made Up Date.
?T S11/9/1

11/9/1 (Item 1 from file: 561)

06245421

CHARTER AEROSPACE LIMITED
WAKEFIELD HOUSE
32 HIGH STREET
PINNER
MIDDX HA5 5PW

Registered Company Number: 02421561
Country: ENGLAND & WALES

Date of Incorporation: 11Sep1989
Accounting Reference Date: 30May
Date of Last Return: 25Sep90
Date of Annual Account: 31May90

This is a LIVE company

Company Type: Private limited with share capital
Account Type: SMALL COMPANY
Nominal Capital (Sterling): 1,000
Issued Capital (Sterling): 2

LAST UPDATE AND TRANSACTION
21Nov90 Annual Return Made Up Date.
?LOGOFF

04dec90 15:58:01 User211075 Session A79.2
$0.66 0.006 Hrs File30
$0.66 Estimated cost File30
$0.58 0.008 Hrs File262

#16

→ For Jim H.

File / Honeywell

IGA LOG #: 474

DATE/TIME: 02/05/91/

APPOINTMENT REQUEST

VISIT: __ __ INTERVIEW: __ __ MEETING: X SPEECH: __ __ OTHER: __ __

DUSD/TSP: X ADUSD/TSP: X DIRECTOR: __ __

Referred by:

Key Person(s)/Title: RON BARNHART (VP - GOV'T SYSTEMS MARKETING, DALLAS BURNS (VP - CORP SOLID STATE PRODUCTION) AND COLEMAN*

Organization: HONEYWELL

Requestor/Telephone: RON BARNHART (VP - WASHINGTON OFFICE)/(703) 827-3566

Subject: PRESENTATION OF HONEYWELL CLOSING INVESTIGATION REPORT ON FAE TECHNOLOGY TRANSFER

Date: 02/11/91 Time: 1400 Place: SP CONFERENCE ROOM, DTSA

DTSA Staff to be Present*: MALOOF, MENAS, KONFALA, RICHEY, GRIFFIN

IGA Comment/ Recommendation: RECOMMEND MR. RUDMAN (GREET IF AVAILABLE) AND MR. SULLIVAN HOST THE MEETING SINCE MR. SULLIVAN HOSTED THE 11 DEC 90 INITIAL DISCUSSION WITH HONEYWELL.

*HICKS (COVINGTON & BURLING)

IGA Action Officer: ROSEN/37112

FRONT OFFICE USE

Calendar is clear: ____________

Alternate date: ____________

MA has seen: ____________

DUSD/TSP

Accept__________

Decline__________

ADUSD/TSP

Accept__________

Decline__________

Comments: ____________

cc: All Directors, MA, SA

*IF YOUR DIRECTORATE HAS NOT BEEN INVITED TO ATTEND THIS EVENT AND YOU

OFFICE OF THE UNDER SECRETARY OF DEFENSE

WASHINGTON, D.C. 20301-2000

T50

POLICY

MEMORANDUM FOR DUSD/TSP
ADUSD/TSP
ALL DTSA DIRECTORS

SUBJECT: Honeywell Fuel Air Explosives -- INFORMATION MEMORANDUM

A meeting is scheduled for Monday, 11 February 1991, at 1400 hours to listen to an overview of Honeywell's Executive Summary of the two reports written as a result of their investigation into their suspected involvement in Fuel Air Explosives. One report is by the Honeywell commissioned law firm of Covington and Burling; the other is Honeywell's own internal report.

Honeywell is planning a press release soon after they meet with us. Ron Barnhardt (VP Washington Office) delivered a copy of the draft press release to us today, and asked for our comments. As currently written the draft press release states "The Department of Defense concurs with the investigation results".

At the moment this statement is unacceptable, since we have not finalized our investigation. I have scheduled a prebrief for the Honeywell meeting with Mr. Rudman on Monday at 1330 hours.

Frank

Frank T. Bray
Director, Industry and Government Affairs
Defense Technology Security Administration

Attachment
as

From the Desk of

Ron Barnhart
827-3566
VA20-A530

Honeywell Attendees

02/11/91 DIBA Mtg. — 2:00 PM

- Ron Barnhart – V.P. Business Development
- Dallas Burns – V.P. Technology
- John Stenger – MGR, Govt Systems Mktg.
- Coleman Hicks – Covington & Burling
- Tom Johnson – " "

Honeywell

From: Susan M. Eich
For: Honeywell Inc.
Honeywell Plaza
Minneapolis, MN 55408
(612) 870-6730

For approval
draft 8
FAE Group
Alliant
Hicks

HONEYWELL AND ALLIANT TECHSYSTEMS ANNOUNCE RESULTS FROM INVESTIGATION INTO FUEL-AIR EXPLOSIVE STUDIES

MINNEAPOLIS, Feb. xx -- Honeywell and Alliant Techsystems today announced the results of two investigations into Honeywell's 1984 sale of two fuel-air explosives [FAE] studies to the Swiss company IFAT. The investigations resulted from Honeywell Chairman and Chief Executive Officer James J. Renier's commitment, when the story broke last November, to "get to the bottom" of allegations concerning the nature of the studies and whether they may have reached Iraq.

One investigation was an independent two-month effort by the law firm Covington & Burling to determine what occurred in 1984. The second was a technical analysis of the two studies by a team of engineers from Honeywell and Alliant Techsystems, the defense business that Honeywell spun off in September 1990.

Summaries of the two investigations, copies of which are attached, indicate that:

o There is no evidence of any sale or other transfer of Honeywell FAE technology to Iraq.

o There is no evidence of any transfer by Honeywell, directly or indirectly, of any other military technology to Iraq. Honeywell has never sold or tried to sell military technology to Iraq.

-more-o The two studies consisted of previously published, unclassified information that was of little practical military value and were not the source of any FAE capability Iraq may have;

o Appropriate management approval was not obtained for sale of the two studies. Honeywell's internal policy required executive approval for military sales to the Middle East, including Egypt, IIFAT's customer for the studies.

o There is no evidence that the company, or any of its employees, tried to circumvent the law.

Based on these findings, and on discussions with the Pentagon, Honeywell and Alliant believe that no employees acted illegally or in bad faith. On its own initiative, Honeywell has provided a summary of its findings to the Pentagon. ~~The Department of Defense concurs with the investigation results~~.

Honeywell and Alliant are using this experience to re-emphasize to employees the importance of high ethical standards and adherence to policy. However, the companies have decided that disciplinary action would be inappropriate with regard to the infraction of internal company policy. This decision considered the nature of the infraction, and the period and circumstances under which it occurred.

Honeywell is a global controls company that provides products, systems and services for homes and buildings, industry and aviation and space. The company had 1989 sales of $6.1 billion.

Alliant Techsystems supplies high-quality precision armament, ordnance, marine and information storage systems to the U.S. government and its allies. In 1989, the company had revenues of $1.3 billion and net income of $42 million. Headquartered in Minnesota, Alliant Techsystems employs 7,600 people throughout the United States.

-O-

1991

HONEYWELL Interoffice Correspondence #17

Date: January 21, 1991

Subject: FAE DATA REVIEW

To:	R. H. Barnhart*	VA20	From: D. D. Burns
			Org: Corporate
cc:	D. R. Bergerson	MN12-5104	HED: MN12
	R. Boncy	MN12-8251	MS: 5204
	J. Crawford	MN12-8251	HVN: 870-2870
	R. H. Cress	MN12-5219	
	C. O. Larson	MN12-5107	

*Receiving attachments

Ron:

As you know, we had previously characterized the DSD FAE report as a generic "cut and paste" assembly of FAE information that was readily available in the open literature. That conclusion was based on a review of a large sample of the source reports listed in the bibliography. We also conducted a library search to verify the position taken in the report that all of the sources used were unclassified, open literature sources.

Last week, we received the final results of the library search and found that three sources listed in the bibliography are distribution limited in some way. None are classified or "NOFORN". The problematical references are those listed on Attachment #1. We then conducted a review to determine what, if anything, from these sources was used in the preparation of the DSD report. Our findings to date are discussed in the Attachment #2 memo to me from Dick Cress. In summary:

#26 - Very generic, literature survey data search conducted by a firm in the Netherlands.

#177 - Not available - we're trying to get a copy.

#208 Two curves in the DSD report appear to have been taken directly from this source (see Cress memo).

Our immediate concern is with reference #208. Since the document contained no internal distribution limitation statements, we have no way of knowing whether the particular material used in the DSD report was of a sensitive nature.

Action Request

Please convey this new information to our contacts at DTSA. I'll let you know what we find out about reference #177 when we get it. In the meantime, we want to keep DTSA fully informed on our status. Since DTSA seems to be running ahead of us in most aspects of the FAE inquiry, they may already have made some judgments about these reference materials. If so, please let me know.

DDB/bjs
Attach.

Dal Burns

Attachment 1

26 Coevert K et al, Fuel-air-explosives, Explosion of unconfined vapour DDC Users Only
clouds, (Literature Survey). Report TL-1975-2, TDCK-65977 (1975).

See item 72 of CSO.

Distribution Limit Statement: DDC Users Only

177 Baker M, Kratz H.R., Waddell J.L., Sedgwick R.T., Concepts for Improved Fuel-Air-Explosives, Report Number SSS-R-76-3005 (1976).

Distribution Statement: Limited to Govt. agencies only. Others to: ARPA/TIO, 1400 Wilson Blvd., Arlington, VA 22209

208 Contents of this section are based on material presented in Investigation of the Aerodynamic Breakup of Viscoelastic Liquids, Phase I Subsonic Dissemination, W.H. Anderson, N.A. Louis, and G. Lalongo, Report Number ADB020985 (1977).

Distribution Statement: Limited to Govt. Agencies and their Contractors.

Honeywell Interoffice Correspondence

Date: 18 January 1991

Subject: **FAE REFERENCE DATA REVIEW ..... INTERIM STATUS REPORT #6**

To: D. D. Burns	MN12-5219	From:	R. H. Cress
		Organization:	Strat & Bus Dev
cc: R. R. Boncy	MN12-8251	HED:	MN 12
J. E. Crawford	MN12-8251	MS:	5219
C. O. Larson	MN12-5107	Telephone:	870-3841

Attachment Copies of Pages 33 and 34 from the Document Listed as Referenced #208 in the DSD FAE Report Bibliography.

BACKGROUND

Dallas, in response to your request yesterday afternoon, I obtained copies of two limited-distribution documents (*DSD FAE Report Bibliography reference #26 and #208*) from the microfiche files in the Alliant Techsystems library at Edina. I visited the library late yesterday and obtained a copy of the document listed as Reference #26 in the DSD FAE Report. The library could not provide me a copy of the second document, Reference #208, until this morning.

I looked over the Reference #26 Document last night, and I have concluded it is probably not a problem; however, some additional legal/library work is need to finalize this conclusion. I wrote-up my conclusions and addressed the additional work regarding #26 earlier this morning, and they are provided as the second conclusion in this memo.

I looked over the Reference #208 document later this morning, and I have quickly concluded it is a potential problem. Because it may be a problem, I wanted to provide you with a preliminary input right away. The following paragraphs present my initial conclusion regarding Reference #208. More work is needed to comprehensively review #208 and accurately compare it against information in the DSD FAE Report.

INITIAL CONCLUSION ..... Reference #208 is a potential problem

- Regarding DSD Bibliography Reference # 208:

  This document represents a potential problem to Honeywell. It was authored and published by the Chemical Systems Laboratory under the U. S. Army Armament Research and Development Command at Aberdeen Proving Ground. It has specific limited-distribution markings and statements which include:

"Distribution limited to US Government agencies only because of test and evaluation: August 1977. Other requests for this document must be referred to Director, Chemical Systems Laboratory, Attn: DRDAR-CLJ-1. Aberdeen Proving Ground, Maryland 21010." *(on the cover and in block 16 of the included DD Form 1473)*

"The information in this document has not been cleared for release to the general public." *(on page i)*

As of this morning, I have found two instances where information in #208 was included verbatim in the DSD report, as follows:

1. The information from Figure 6 on page 32 of #208 is shown verbatim on page 43 of the DSD FAE Report.

2. The information from Figure 7 on page 33 of #208 is shown verbatim on page 44 of the DSD FAE Report.

As you requested. copies of pages 32 and 33 from #208 are provided in the Attachment to this memo.

Additionally, while I have not had the time necessary to comprehensively compare the text and mathematical equations in #208 with the DSD FAE report, I believe that some of the theoretical observations and mathematical equations shown on pages 39 through 55 of the DSD FAE report may be also based, in part, upon the information in #208, as well.

INITIAL CONCLUSION ..... Reference #26 <u>is not</u> a problem

- Regarding DSD Bibliography Reference # 26:

This document appears to be a standard FAE-related literature survey, and it was conducted in 1975 by a technical laboratory in The Netherlands. It contains general information and some theoretical data on FAE, and it could have been reviewed by the DSD authors; however, with the potential exception of the blast graph discussed below, I did not see any direct quotes from #26 in the DSD FAE Report. There is a list of 37 references listed on pages 29 through 32 of #26. A review of this Reference list does not indicate to me that any of the references were classified. I believe that the information contained in #26 is probably too general in nature to directly support design of an FAE weapon; however, someone with direct FAE technical knowledge should also review #26 to verify my opinion.

Regarding the blast graph in Figure 4 on page 21 of #26 .... a graph is shown indicating Peak Overpressure vs. Distance for FAE-mixture and high-explosive blasts. This graph is similar to, but not the same as, the blast graph on the left-hand side of Figure 6.1 on page 79 in the DSD FAE Report. The graph in #26 does not include a comparison curve for a nuclear blast, which was a somewhat worrisome comparison made in the DSD FAE report figure. The #26 graph was based on a 1966 source (*"ref. 30" indicated in the Figure 4 caption in #26*). With the exception of the limited-distribution marking on the DTIC printout, as discussed below, I do not believe that the information per se in #26 represents a problem.

Regarding the Limited-Distribution Marking on the DTIC printout .... #26, itself has no limited-distribution markings at all, that I can see. The DTIC printout that you gave me yesterday indicates a "Block 22" distribution limitation of "DDC USERS ONLY" for #26. I see no specific limitation regarding "NOFORN" on #26 or the DTIC printout. It is not clear to me that the "DDC USERS ONLY" limitation would constrain a "DDC User" from passing on the document to "anyone with appropriate need," after they have obtained it from the DTIC. I do not have the background to evaluate this legal/regulation-type issue effectively. It needs to be assessed by the appropriate library and legal people at Alliant and Honeywell. I believe that direction/coordination of this assessment should be an action item for Jennifer Crawford.

ATTACHMENT ..... Copies of pages 32 and 33 From the Document Listed as Reference #208 in the DSD FAE Report Bibliography

18 January 1991

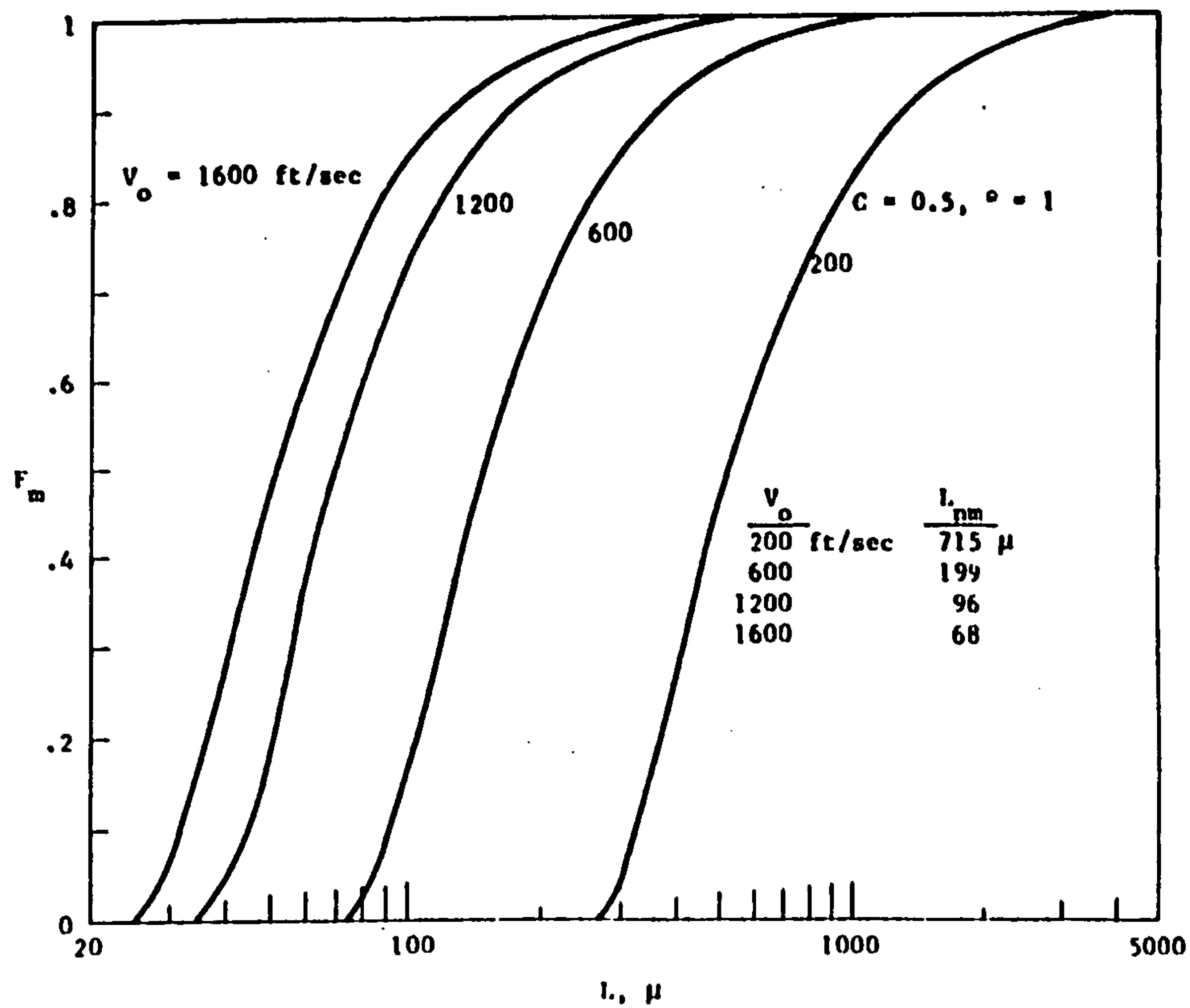


Figure 6. Effect of Relative Velocity on the Number Fraction Distribution.

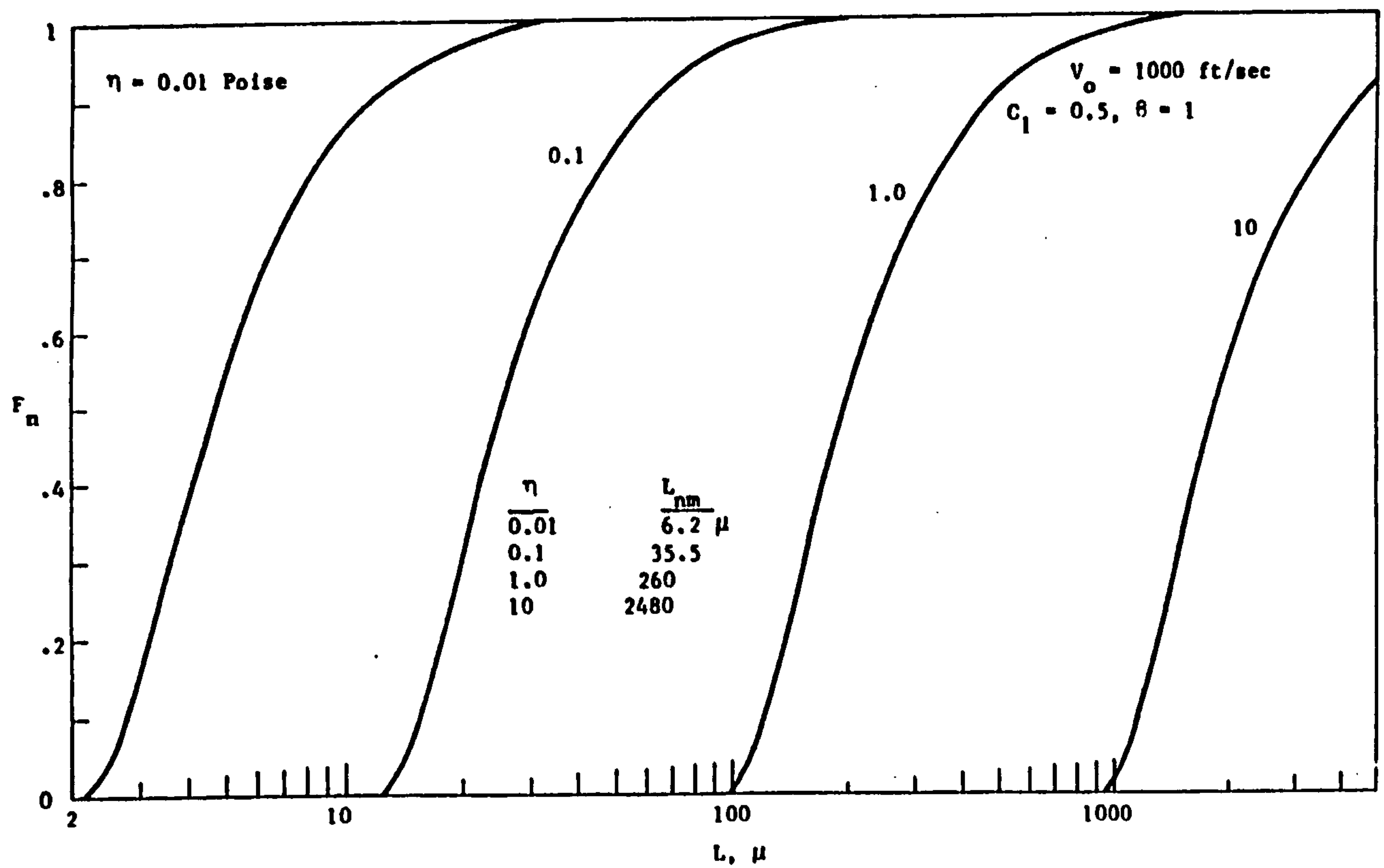


Figure 7. Effect of Fluid Viscosity on the Number Fraction Distribution.

HONEYWELL Interoffice Correspondence #18

Date: December 17, 1990

Subject: INFORMATION FOR CAPTAIN JIM HUFF, USN/DTSA

To: R. H. Barnhart VA20

cc: R. Boncy MN12-8251
J. Crawford MN12-8251

From: D. D. Burns
Org: Corporate
HED: MN12
MS: 5204
HVN: 870-2870

This is a preliminary response to some of the questions raised in our DTSA meeting of December 11th, and in a telephone discussion I had with Captain Huff on December 13th.

1) What was Honeywell paid for the DSD and UK FAE studies?

Answer: The DSD study was billed to HCSL (Bracknell, UK) at $72,000.00. We haven't yet determined the amount of the HCSL billing to IFAT, but we have found evidence that the price was quoted in May 1984 at $159,425.00.

2) What do we know about the current whereabouts of the HCSL people who were principals in the FAE study effort?

Answer: Bracknell's response, via Colin Millar, is attached. I'm advised that Bracknell is still reviewing archives. We will send additional information as it becomes available.

3) What is the history of technology transfers from Honeywell to Hunting Engineering LTD?

Answer: Our file search has yielded the attached summary of technology transfers since 1980.

Please send this information on to Captain Huff. Thank you.

Dallas Burns

DDB/bjs
Attach.

CHARTER AEROSPACE LIMITED

Registered Office:	Wakefield House 32 High Street Pinner Middx. HA5 5PW.
Company Address:	Charter Aerospace Limited Charter House, 426 Avebury Boulevard, Milton Keynes, MK9 2HS. Tel: 0908 666646
Directors' Home Address:	Keith Gilbert Smith Greenhouses Benhams Park Marsh Benham Newbury Berks. RG16 8LU. Margaret Florence Smith (As above) Tel: Ex-Directory No.

David A. Venables
The Coach House
Upper Farm
Upper North Wraxall
Chippenham
Wilts. SN13 7AG.

Tel: 0225 891026 (Home)
0272 260794 (Work)
(Bristol Age Care)

Joined Honeywell 12.10.81 as Marketing Director, promotion to Director, Business Development on 1.10.82, left Honeywell 13.5.88.

Brian Gowers
2 Hornbeams,
The Street,
Swallowfield,
Reading, Berks.

Tel: 0734 882954 (H)

Dr. Gareth Thornton

Joined Honeywell 22.8.83 as Group Leader, Operations Analysis, left 28.2.85.

Michael Webb (deceased 1985)

Job Title was Manager, Defence Systems, Electronics.

Graham Ruthen
Honeywell Aerospace & Defence Ltd.,
12b Alfred Street,
Westbury.
Wilts.

Tel: 0373 858066 (W)

R. Colin Millar
Bottom Barn,
Manor Farm,
East Hagbourne,
Oxon. OX11 9ND.

Tel: 0235 813847 (H)
Tel: 0344 416216 (W)

Hunting Engineering Ltd.,
Reddings Wood,
Ampthill,
Bedford, MK45 2HD.

Tel:

No info on Linda Yodr or Barry Greig (Gregg) - appear not to have been employees of Honeywell.

Searches have been carried out at Newhouse archives and Bracknell archives but no information has come to light. Also searches carried out Leafield Engineering (formerly Honeywell Aerospace & Defence Ltd.)

Bracknell HR department have also checked records but no information is available.

Accounts have gone back through their records re trade carried out between Hunting Engineering and Honeywell Control Systems. Approximately £3,062 of business during 1989/1990. Unable to ascertain amount of business before that time but further searches are being carried out by Accounts Dept.

No record of any business between HCSL and IFAT.

#19

H O N E Y W E L L Interoffice Correspondence

Date: December 7, 1990

Subject: REQUEST FOR INFORMATION BY DEFENSE TECHNOLOGY SECURITY ADMINISTRATION

To: R. R. Boncy

cc: D. R. Bergerson
C. O. Larson
M. J. O'Neill
R. A. Reed

From: J. E. Crawford
Org: General Counsel
HED: MN12
MS: 8251
HVN: 870-6182

Lieutenant Fritz Vollkommer is employed by Navy Intelligence but is on assignment to the Defense Technology Security Administration. After three calls to Martha Cooper, he was referred to me to answer his questions. On 5 December 1990 he called requesting the following:

1. All information that Keith Smith got from Honeywell on inertial guidance, FAE, and cluster bombs, as well as whatever else to which he had access.

2. He asked for a list of everyone who had worked with Warde Wheaton. He later scaled that down to department heads and everyone who worked for Mr. Wheaton in the FAE and cluster bomb areas.

I told him that I would get back to him with a status on 7 December 1990.

JEC:bk Jennifer/bk
JC12070A

D000048

#20

Honeywell

JENNIFER E. CRAWFORD
Corporate Compliance Counsel

December 7, 1990

Lt. Frederick C. Vollkommer
Technology Security Operations
400 Army Navy Drive, Suite 300
Arlington, VA 22202

Lt. Vollkommer:

This will confirm our telephone conversation of 7 December 1990 in which we discussed Honeywell's response to your verbal request of 5 December 1990.

1) I asked whether you would please confirm your request in writing. You will advise me whether you can do this.

2) You requested that we search for what information Keith Smith received from Honeywell on inertial guidance, FAE, and cluster bombs. At Honeywell, we are searching for such information particularly in Inertial Guidance which is still a Honeywell business. To date, we have located the 1984 FAE Warhead Analysis Report which is enclosed with this letter.

3) I referred you to Mr. Chuck Erickson of Alliant Techsystems who would have access to information relating to FAE and cluster bombs.

4) You asked for a list of Mr. Ward Wheaton's department heads. A list of such people in 1984 is also included with this letter.

5) You asked for names of everyone who worked for Ward Wheaton on FAE or cluster bombs. As we discussed, Alliant would be the source of such data.

We will keep you advised of our progress in this matter. If you have any questions, please call me on (612) 870-6182.

Sincerely,

Jennifer Crawford
Corporate Compliance Counsel

JC:dd

Enclosures (3)

For this wrap up report, the primary source document is the OSD report ...
entitled "FAE Warhead Analysis Final Report"
dated December 1984
prepared by Mission Analysis Group, Honeywell DSD

Symbol Definitions for Verified Public References
D# - verified in report, # referenced in OSD bibliography
H# - verified in abstract, # referenced in HCSL bibliography
F# - not yet verified in report, # referenced in OSD biblio y
L# - not yet verified in report, # referenced in LATIS list
pp - page number of referenced document
+ - continued on pages following pp
VB - verified verbatim from referenced document

Page	Section	TOPIC	DISCUSSION	SPECIFIC QUOTED REF	VERIFIED PUBLIC REFERENCE
1	1	Executive Summary	"Also included were ethylene and propylene oxide because of their demonstrated efficiency as fuel air explosives."	none	D#125 pp 33-1
2	1	Executive Summary	"Other models exist which .... or whose distribution is restricted (the China Lake 'Josephson' model for example). These models were not dealt with in the study although the Josephson model is compared here for reference."	none	H# 18 of 77 L#s: 155 thru 159
4	2	Introduction	"Indeed, no meaningful analysis of an explosive weapons system can be made without a careful treatment of static and dynamic over pressure and impulses, separately and together. .."	175	D#125 pp 33-8
5	3.2	Fuel Air Explosive Requirements	..."there is a nominal net warhead payload limit of three hundred and sixty kilograms ..."	none	F# PO, F# Customer-provided specification
6	3.2	Fuel Air Explosive Requirements	"FAE fuels with the highest free energy decreases for the explosion process are the most desirable"	none	D#125 pp 33.9 10
7	3.3	Fuel Sources	.. "ethylene and propylene oxides" ... "demonstrated effectiveness in military FAE weapons."	none	D#125 pp 33-1
17	3.5.2	Energy of Explosion	"An alternative to the troublesome evaluation of the line integral above is to make an overall thermodynamic analysis directly in terms of thermal values of pertinent thermodynamic properties."	none	D#125 pp 33-7/Table II F# 208
25	3.53	Entropy of Explosion	"Another limiting situation is an explosion in which negligible amount of gases are produced ... This situation is approached in lightning and nuclear explosions."	none	F# general physics
32	3.53	Entropy of Explosion	"It is remarkable, in fact, that equation 3.6-1 can give an experimentally verified answer within a factor of 10."	none	F# general physics
32	3.53	Entropy of Explosion	"There is some indication in the literature that the more energetic the detonation charge, the more likely a given fuel will detonate."	none	D# 156 pp 1191
32	3.53	Entropy of Explosion	"The initial list contained 19 fuels, 8 of which have been demonstrated to detonate ..."	Table 3.4 (see table)	Not included in the HCSL report , H# 41 of 77 F#s 159 163 172 199
34	3.6	Fuel Experimental Data	In Table 3.4 ... "Propylene Oxide" ... "Demonstrated Detonability" .	159 163 172 199	D# 159 pp D#188 pp 127 D#125 pp 33 1, 11 + D# 163 pp 9 F#s 172,199
34	3.6	Fuel Experimental Data	In Table 3.4 ... "Propylene Oxide" ... "Calculated Energy of Explosion" ...	Section 3.5.2	D# 159 pp D#125 pp 33-7 Table II F#163 , F#206
35	3.7	Fuel Considerations	"The fuels and the necessary figures needed to obtain the total specified warhead energy are listed in Table 3.4."	none	D#125 pp 33 7 Table II
36	3.7	Fuel Considerations	"In real terms, diesel fuel, kerosene, and gasoline are the same." (regarding combustion chemistry)	none	D#60 pp 6
36	3.7	Fuel Considerations	"may even be better than the first group (propylene oxide and decane especially)" .	none	D#188 pp 127 D#125 pp 33-1,7 Table II D# ("#300" pp 4, 12 see working copy)
38	4.1	Aerosol Definition and Characteristics	"... the evaporation rate of even higher pressure fluids is too slow for FAE weapons."	none	F# general physics, F#207
39	4.2	Cloud Dispersion	"FAE clouds are usually dispersed by placing a small explosive burster charge along the axis of the cylinder."	none	D#125 pp 33 3
42	4.2	Cloud Dispersion	Table 4.2 ... "Stoichiometric (Detonation) Radii of Fuels"	none	D#125 pp 33-16 Figure 17
52	4.2.3	Cloud Dispersion and Size	"The toroidal case will give a higher peak over pressure over a larger area than the hemispherical case for a fixed quantity of fuel."	none	D#125 pp 33-9/Figure 8

[redacted]

For this wrap up report, the primary
source document is the DSD report ...
entitled "FAE Warhead Analysis F[illegible]"
dated December 1984
prepared by Mission Analysis Group, Honeywell DSD

Symbol Definitions for Verified Public References
D# - verified in report, # referenced in DSD bibliography
H# - verified in abstract, # referenced in HCSL bibliography
F# - not yet verified in report, # referenced in DSD biblio y
L# - not yet verified in report, # referenced in LATIS list
pp page number of referenced document
\+ continued on pages following pp
VB - verified verbatim from referenced document

Page	Section	TOPIC	DISCUSSION	SPECIFIC QUOTED REF	VERIFIED PUBLIC REFERENCE
52	4.2.3	Cloud Dispersion and Size	"For example one might find substantial 'spikes' superimposed on a hemispherical cloud that are artifacts of the rupture seams in the fuel canister However it appears from the literature that this may not be a serious problem."	none	D#60 pp 13, 14 F#207
52	4.2.3	Cloud Dispersion and Size	"... average speed is on the order of 80 meters per second." (the piston expansion velocity)	none	F# general physics F#207
54	4.2.3	Cloud Dispersion and Size	"... detonation radius ... Of special interest in this case is decane with a 29% larger rs than diesel fuel."	none	D# ("300" see working copy) F#60
55	4.3	Burster Charge	"The burster charge used for FAE dispersal has been composed of several explosives." ... "TNT, RDX" ... "C 4" "The quantity required" ... "generally amounts to three quarters to one percent of the fuel mass."	none	D#125 pp 33-3 Figure 2 D#158 pp 1193
56	4.3	Burster Charge	Figure 4.5 "Cloud Radius vs Fuel Density for 80 Meter/Second Average Dispersion Velocity"	none	Not included in the HCSL report F# general physics
57	4.4	Burster Charge	"Typical burster charges driving a dispersive 'gas piston' amount to one percent of the fuel mass and drive the fuel radially outward with an average speed on the order of 80 meters per second."	none	F# general physics (80 meters/sec) D#125 pp 33-18
57	4.4	Burster Charge	"The fuel cloud will also have spikes and other inhomogeneities as artifacts of the war head structure."	none	L#63 D# 60 pp 1
57	4.4	Burster Charge	.. "Accordingly, we may conclude that a 1% of fuel mass TNT burster charge will drive the fuel to the stoichiometric radius at which point it can be optimally detonated."	none	D#125 pp 33-18
58	5.1	Aerosol Cloud Detonation Background	"It is well known ... detailed investigations ... influence of the tube walls cannot be neglected ... For small diameter tubes the observed decrease in velocity ... On the other hand, it is also observed ... fails once it emerges ..."	209	H# 70 of 77 entire page is VB from D#209 pp 51 L#63
59	5.1	Aerosol Cloud Detonation Background	"A possible relation between the spinning detonations in tubes and the detonability limits has been discussed ..."	209	H# 70 of 77 entire page is VB from D#209 pp 52
60	5.1	Aerosol Cloud Detonation Background	"However, it has been shown that acoustic and non-linear perturbations can be amplified ..."	209	entire page is VB from D#209 pp 53
61	5.1	Aerosol Cloud Detonation Background	"associated ... detonation wave is not understood."	209	most of page is VB from D#209 pp 53,54
64	5.3	Chemical Detonation	"The possibility exists of chemical detonation of a FAE warhead. Laboratory tests have shown that light FAE hydrocarbon fuels as well as diesel oil can be detonated by the injection of elemental fluorine, chlorine trifluoride or bromine trifluoride into the aerosol cloud." .. "It is important to note however that this has not yet been achieved with a deployable FAE weapon."	none	D#60 pp 1 D#165 pp 1 D#209 pp 1 H# 32 of 77 H# 37 of 77
65	5.4	Detonation Energy and Delay	"Experiments have established that the average cell size is constant for a self sustained detonation."	none	F#157
66	5.4	Detonation Energy and Delay	"A rule of thumb that appears successful suggests that a minimum FAE detonation energy is that which is liberated from one or two percent of the fuel weight of TNT."	none	D#125 pp 33-4, 8, 14, 18
68	5.4	Detonation Energy and Delay	"delay time" .. "is an important parameter whose optimum value can only be determined experimentally."	125	D#158 pp 200 D#60 pp 6 (chemical) D# 209 pp 2 50 L# 160 pp 290 D#("301" pp 2, 50 see working copy)
69	5.4	Detonation Energy and Delay	"Sedgwick and Kranz (125) are the only published workers in the open literature known to the author to have studied this problem." (delay time) "Elsewhere delay times for conventional FAE bombs of ... have been reported ..."	125 172	D#125 pp 33-1 + H#'s: 18 of 77, 32 of 77, 45 of 77 F#172
69	5.4	Detonation Energy and Delay	"For our case, ..." ... "noting that the average speed (S) of the expanding fuel cloud will be on the order of 80 meters per second." "which gives a rough detonation delay range of 0.120 seconds to 0.170 seconds."	none	D#125 pp 33-1 Table I F#209 F#172
69	5.4	Detonation Energy and Delay	"... probable maximum delay times feasible ... propylene oxide beyond 0.180 seconds."	125	D#125 pp 33-7,14 F#209 H#'s 25 of 77, 29 of 77, 31 of 77

For this wrap up report, the primary source document is the DSD report
entitled "FAE Warhead Analysis Final Report
dated December 1984
prepared by Mission Analysis Group, Honeywell DSD

Symbol Definitions for Verified Public References
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H# - verified in abstract, # referenced in HCSL bibliography
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Page	Section	TOPIC	DISCUSSION	SPECIFIC QUOTED REF	VERIFIED PUBLIC REFERENCE
70	5.4	Detonation Energy and Delay	Table 5.1 ... "Variations in Delay Time (Propylene fuel)"	125	VB D#125 pp 33-7 Table
72	5.5	Multiple Clouds & Mutual Detonation	"The detonation transfer experiments involving two FAE clouds were performed for the purpose of determining the maximum allowable space between canisters and the maximum allowable cloud dwell (detonation delay) time. In this first series of experiments the burster charges of each canister were detonated simultaneously. Each canister comprised 2 gallons of propylene oxide fuel with a length to diameter ratio, l/d, of two. For instance, with a 8.53 m spacing between the canisters and a cloud dwell time of 120 ms the detonation of one cloud did not cause the detonation of the second cloud. Table 5.3 " Experiments"	none	D#125 pp 33-10+, VB pp 33-11 Table IV
73	5.5	Multiple Clouds & Mutual Detonation	"... another test involved the dissemination and detonation of a seven canister array ... [illegible]"	none	D#125 pp 33-14+
74	5.5	Multiple Clouds & Mutual Detonation	Figure 5.3 ... "... detonation transfer experiments ..."	none	VB D#125 pp 33-12/Figure 11
75	5.6	Summary Multiple Clouds	Figure 5.4 ... FAE Clouds ... form a single cloud ... approximately 14 m"	none	VB D#125 pp 33-16/Figure 17
76	5.6	Summary Multiple Clouds	Figure 5.4(duplicate Figure number in DSD report) ... "Burster Delay ... P.O. Fuel"	none	VB D#125 pp 33-13/Table V
77	5.6	Summary - detonation charge	"... experience has shown that the detonation charge is more typically about 1% of the fuel mass. This suggests that about 4 kilograms of TNT would be required for the E2D warhead ... Alternative means of detonation using halogen compounds have been achieved in laboratory experiments but are so underdeveloped at this time that a significant developmental program would be required to produce a deployable device."	none	D#125 pp 33-4, 6, 14, 18 F#209 F# PO, F# Customer provided specification
77	5.6	Summary - detonation charge	"... scaling laws suggest that detonation of the E9M warhead could be delayed as long as [illegible] seconds ..."	none	Not included in the HCSL report F# PO, F# Customer provided specification D#125 pp 33-17
79	6.1	Background - Convent'l vs FAE Nuclear	Figure 6.1 ... "Qualitative comparison of blast parameters of conventional, nuclear and FAE [illegible]"	none	H# 47 of 77, H# 51 of 77 D#142 pp 1, 40 D#188 pp 9 D#190 pp 3, 178+
79	6.1	Background - Convent'l vs FAE Nuclear	"The most significant difference between conventional high explosives and the others [illegible] produce peak over pressures over an extended region. Also, the Over pressure [illegible] faster with conventional explosives than with nuclear and FAE."	none	D#190 pp 178+
81	6.2	Scaling Laws	"Full scale tests have shown this relationship between distance and energy yield to hold for yields over a very large range. Thus, cube root scaling amy be applied with confidence ..."	none	D#125 pp 33-17
82	6.3.1	Model Selection	"This is a reasonable assumption for an experimental situation and may even be approached on occasion with conventional FAE bombs such as the CBU-55B."	none	Not included in the HCSL report F#203, F#198
82	6.3.1	Model Selection	"In addition, out to the stoichiometric, or detonation radius (rs) the pressure is truncated at [illegible] per square centimeter to represent the observed pressure within an exploding FAE cloud."	none	Not included in the HCSL report F#203, F#198
85	6.3.3	Brode Model (Modified)	"The modified Brode model for nuclear blast simulation may be expressed as follows .... and W is in kilotons equivalent yield. It should be pointed out that W in equation 6.3.3 is for an equivalent nuclear detonation. However, FAE fuels are k times more energetic than TNT so we get W/2 = kWck, ... This model approximates the FAE case if one truncates the over pressure at 260 psig ..."	160	L#156 pp 93 F#60 L#'s: 42, 1029, 1130
90	6.5	Blast Summary	"On the basis of this preliminary study, we would suggest assuming a range of f values from 0.05 to 0.5 and carrying out blast calculations and kill probabilities accordingly."	none	Not included in the HCSL report F#'s: 23, 198, 203
91	7.1	Single vs Multiple FAE Canisters	"Detonation of multiple smaller FAE canisters containing a fixed total amount of fuel will cover a greater area with a minimum specified over pressure than can be covered by the detonation of the same amount of fuel in a single large canister."	none	Not included in the HCSL report D#125 pp 33-16 Figure 17
92	7.1	Single vs Multiple FAE Canisters	"An exact analytical expression for C(n) is probably not possible given the practical variables it represents, but it probably looks something like C(n) = Nvlh(Blo(d/u)s)"	none	L#129

For the wrap-up report, the primary source document is the DSD report __
entitled: "FAE Warhead Analyses Final Report
dated: December 1984
prepared by: Mission Analysis Group Honeywell DSD

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Page	Section	TOPIC	DISCUSSION	SPECIFIC QUOTED REF	VERIFIED PUBLIC REFERENCE
92	7.1	Single vs Multiple FAE Canisters	.. "For the most practical cases where n=3 and 7 we get f(v) equal to 0.85 and 0.78 respectively."	App B	Not included in the HCSL report L#468
93	7.1	Single vs Multiple FAE Canisters	"Putting this and n=7 bomblets in equation (7.1-4) gives a kill area advantage of 1.1 over the single canister case. Given the additional complexities of a multiple canister system and the reduced reliability probably accompanying it we would favor the single large warhead."	none	Not included in the HCSL report L#468
122	App B	Peak over pressure vs. Distance	"Also included is a comparison of the modified Brode model to the 'Josephson' (China Lake) model for 400 kg of propylene oxide."	none	Not included in the HCSL report L#42

#21

HONEYWELL Interoffice Correspondence

Date: February 7, 1991

Subject: FAE REPORT ASSESSMENTS
ATTACHMENTS:

1) FAE REFERENCE DATA REVIEW, R. H. CRESS, 6, FEBRUARY, 1991
2) LETTER REGARDING FAE EXPORT REVIEW, K. S. KOZAK (ALLIANT TECHSYSTEMS) TO JENNIFER CRAWFORD (HONEYWELL, 16 JANUARY, 1991
3) SPECIAL STUDY (FAE), M. M. GARRISON (ALLIANT TECHSYSTEMS), 16 JANUARY 1991

To: C. O. Larson MN12-5107

cc: K. Bachman MN12-5153
R. H. Barnhart VA20
D. R. Bergerson MN12-5104
R. Boncy MN12-8251
J. J. Renier MN12-5222

From: D. D. Burns
Org: Corporate
HED: MN12
MS: 5204
HVN: 870-2870

Background

On December 6, 1990, you assigned me to conduct an assessment of the technical content of two Fuel-Air-Explosive (FAE) reports that had been prepared in 1984 under a Honeywell Control Systems Ltd. (HCSL) contract with the Swiss firm, Institute for Advanced Technology, Ltd. (IFAT):

- "DSD report": FAE Warhead Analysis Final Report, December 1984
- "UK report": A Preliminary Study for Development of a FAE Warhead for Application to a Ballistic Missile -- Final Report, November 1984

The DSD report was sent from the U.S. to HCSL in Bracknell, England. It primarily addresses the physical chemistry of fuel-air mixtures and explosions. The author's stated intent was to use only previously published, unclassified reference materials in the preparation of this report. 210 specific references were cited in the report bibliography.

The UK report expanded on the DSD report by adding some general introductory material and several sections that addressed the potential effectiveness of FAE warheads against several hypothetical target types (military air field, naval base, etc.).

Findings

The following summary findings are discussed and documented in Attachments 1, 2 and 3 to this memorandum.

- DSD Report:
  - The report consisted of an integrated compendium of previously published information on the physical chemistry and general principles of FAE. Much of this material (graphs, tables, equations, and entire pages of text) were reproduced without change from the open-literature sources listed in the bibliography.

- A library search of the 210 listed references revealed none that were either classified (i.e. confidential, secret, etc.) or ITAR controlled (i.e. "NOFORN"). Two of the references were found to be marked with distribution limitation statements (i.e. "limited to U.S. government agencies only"), but their use in the preparation of the report was found to be very minimal and, in our judgment, benign.

- The report includes no significant design data descriptive of any existing or prospective FAE weapon system. Such information would include; fuzing sequence and operation, fuel container construction detail, burster charge design, cloud detonation mechanism design, ullage control design, specific inertial and aerodynamic properties, etc.

- The DSD author's background included no significant previous work in FAE technology areas, and there is no evidence that any of the content of the report was derived from Honeywell contract work for the U.S. government.

• UK Report:

  - The added introductory material in Sections 3 & 4 consisted of very general information that was previously released and approved for publication by U.S. government sources.

  - The effects analysis of Sections 6, 7 & 8 appears to have been conducted by HCSL engineers in the UK who had no previous experience in the analysis of FAE weapons. These analyses contain a great many oversimplications and erroneous assumptions, with repect to the treatment of both the design constraints of real world FAE weapons, and the effectiveness of such weapons on a real world battlefield.

  - The report includes no data that discloses the performance capabilities of any existing FAE weapon. Such information would include; specific delivery systems, delivery envelopes and limitations, reliability data, data on interactions between multiple weapon deployments, or test data of any kind on the actual performance of any existing FAE weapon.

<u>Conclusions</u>

The DSD report can be characterized as an open-literature survey of the fundamentals and physical chemistry of FAE. The report was based on the extensive use of previously published, unclassified reference materials. It could have been contemporaneously produced anywhere in the world in 1984, by any qualified scientist with access to the same reference materials.

The UK report is an expanded version of the DSD report. The expansion consisted of previously published introductory material, and the addition of a highly simplistic effectiveness analysis. The added material was generated by HCSL engineers in the UK, and contains errors and oversimplifications of such an extent that the report has no practical military value.

Neither report disclosed information related to FAE contract work

H O N E Y W E L L   Interoffice   Correspondence

Attachment 1

Date: February 6, 1991

Subject: FAE REFERENCE DATA REVIEW

To: D. D. Burns   MN12-5204

From: R. H. Cress Dick
Org: Strat & Bus Dev
HED: MN12
MS: 5219
HVN: 870-3841

Attachment: FAE Reference Verification Matrix, 28 January, 1991

Background

A total of 210 references were cited in the bibliography of the 1984 Honeywell Defense Systems Division (DSD) FAE report. As planned, a sampling approach was then taken to determine whether the data content of the report could be traced to open-literature sources.

Approximately 55 of the 210 references were accessible in the Alliant Techsystems project files, and all of these were initially reviewed for applicability to the verification effort. 35 references were deemed to be likely potential sources and were reviewed in detail. A joint Honeywell/Alliant Techsystems library search was made for all 210 references to determine whether or not any were classified or subject to distribution limitations of any kind. 154 documents were traced for this purpose. These included essentially all references that originated in DoD agencies.

The attached matrix format was developed as the primary tracking mechanism for resolution of the highlighted items and as a detailed, cumulative summary of the results of the sampling verification task. Attached is a copy of this matrix. The right-hand column in the matrix, called "Verified Public Reference," provides a detailed status and results of the public-verification task.

Findings

The results of the verification and library search efforts are summarized below:

- There is no evidence that any of the references contained any classified information.

- None of the references was identified as export controlled (i.e. "NOFORN") under ITAR regulations.

- continued -

- Of the 210 references, only two were found to be marked with distribution limitation statements:

  - Report reference #177, Baker M, Kratz H.R., Waddell J.L., Sedgwick R.T., Concepts for Improved Fuel-Air-Explosives, Report Number SSS-R-76-3005 (1976).

    Distribution Statement: Limited to U.S. Govt. agencies only; test and evaluation: 11 January 1982. Other requests to: ARPA/TIO, 1400 Wilson Blvd., Arlington, VA 22209

    Neither Honeywell or Alliant Techsystems had any record of previous receipt of this document, and we believe, therefore, that it was not used in the preparation of the DSD report. We obtained a copy to support this investigation and were unable to find any direct use of its content in the DSD report.

  - Report reference #208 - Investigation of the Aerodynamic Breakup of Viscoelastic Liquids, Phase I Subsonic Dissemination, W.H. Anderson, N.A. Louis, and G. Lalongo, DDC Number ADB020985 (1977).

    Distribution Statement: Limited to U.S. Govt. Agencies only because of test and evaluation: August 1977. Other requests to DRDAR-CLJ-1 Aberdeen Proving Ground, Maryland 21010.

    Information contained on two charts in the reference #208 document were found to be included in the DSD report (figures on pages 43,44). This information, pertaining to the aerosol behavior of fluid droplets in a high velocity airstream, is not believed to be of a sensitive nature.

Within the attached matrix, we were able to trace numerous graphs, tables, equations, and even entire pages of text, directly to the open-literature sources cited in the report. These findings are summarized in the "Verified Public Reference" column. We found no information that discloses any design detail or performance data (e.g. test results) on any existing or prospective FAE weapon.

Conclusions

None of the documents cited in the DSD FAE report bibliography are classified, and with the minor exceptions of references #177 (not used) and #208 (non-sensitive information), all were readily available from open-literature sources. Information from the open-literature references was extensively used in the preparation of the report, consistant with the stated intention of the author. In fact, the report can be fairly characterized as an "open-literature survey" of the physical chemistry and general fundamentals of FAE.

RHC/bjs
Attach.

HUNTING ENGINEERING LTD. (HEL)
HISTORY OF TECHNOLOGY TRANSFERS
1980 - PRESENT

1. Teaming Agreement dated 9/17/81 with HEL (UK), Dornier (Germany), TRT (France), and Honeywell Inc.

   Technical Assistance Agreement - OMC Approved 10/2/81

   HEL, Dornier, TRT & Honeywell Inc. Agreement expired on 12/31/85 per OMC priviso.

   Technology

   Terminally Guided Warhead for the Multiple Launch Rocket.

   Honeywell Division - DSD

2. Technical Assistance Agreement - 1980-81 timeframe (no signed copy in our files)

   HEL and Honeywell Control System Ltd.

   Technology

   Influence fuze for possible application on the Area Denial Submunition of the JP-233 cluster weapon.

   Honeywell Division - DSD

3. Technical Assistance Agreement - with HEL and Honeywell Inc.

   OMC approved - 8/2/85

   Executed by HEL on 4/12/85
   HI on 4/9/85

   Technology

   Dispenser design and influence fuze technology.

   Honeywell Division - DSD

   - A proprietary Information Agreement and two amendments were also executed by the parties.

   - March, 1987 - HEL forwarded another confidentiality Agreement for signature related to:

     Direct Airfield Attach Command Munition DAACM

Honeywell concerns regarding additional State Department approval.

4. Technical Assistance Agreement with Honeywell DSD and Honeywell Control Systems Ltd. (UK)

   Executed 1/30/84

   No OMC approval in our file -- we're checking.

   Technology

   Warhead Design Analysis for Royal Ordnance Patricroft. (UK)

WRAP UP REPORT

FAE REFERENCE VERIFICATION MATRIX ... 28 January 1991

For this wrap up report, the primary source document is the DSD report entitled "FAE Warhead Analysis Final Report dated, December 1984 prepared by Mission Analysis Group Honeywell DSD

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not yet verified in report, # referenced in LATIS list
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+ - continued on pages following pp
VB - verified verbatim from referenced document

Page	Section	TOPIC	DISCUSSION	SPECIFIC QUOTED REF	VERIFIED PUBLIC REFERENCE
1	1	Executive Summary	"Also included were ethylene and propylene oxide because of their demonstrated efficiency as fuel air explosives."	none	D#125 pp 33-1
2	1	Executive Summary	"Other models exist which .... or whose distribution is restricted (the China Lake 'Josephson' model for example) These models were not dealt with in the study although the Josephson model is compared here for reference."	none	H# 18 of 77 L#s. 155 thru 159
4	2	Introduction	"Indeed, no meaningful analysis of an explosive weapons system can be made without a careful treatment of static and dynamic over pressure and impulses separately and together. ...."	175	D#125 pp 33 8
5	3 2	Fuel Air Explosive Requirements	...."there is a nominal net warhead payload limit of three hundred and sixty kilograms ..."	none	F# PO F# Customer-provided specification
6	3 2	Fuel Air Explosive Requirements	"FAE fuels with the highest free-energy decreases for the explosion process are the most desirable"	none	D#125 pp 33 9 :0
7	3 3	Fuel Sources	. "ethylene and propylene oxides" ... "demonstrated effectiveness in military FAE weapons."	none	D#125 pp 33 1
17	3.5 2	Energy of Explosion	"An alternative to the troublesome evaluation of the line integral above is to make an overall thermodynamic analysis directly in terms of thermal values of pertinent thermodynamic properties."	none	D#125 pp 33 7/Table II F# 206
25	3 53	Entropy of Explosion	"Another limiting situation is an explosion in which negligible amount of gases are produced .... This situation is approached in lightning and nuclear explosions."	none	F# general physics
32	3 53	Entropy of Explosion	"It is remarkable in fact that equation 3 8-1 can give an experimentally verified answer within a factor of 10."	none	F# general physics
32	3.53	Entropy of Explosion	"There is some indication in the literature that the more energetic the detonation charge, the more likely a given fuel will detonate."	none	D# 156 pp 1191
32	3 53	Entropy of Explosion	"The initial list contained 19 fuels, 8 of which have been demonstrated to detonate ..."	Table 3 4 (see table)	Not included in the HCSL report H# 41 of 77 F#s: 159 163 172 199
34	3 6	Fuel Experimental Data	in Table 3 4 .. "Propylene Oxide" .. "Demonstrated Dek nability" ...	159 163 172 199	D# 159 pp # D#168 pp 127 D#125 pp 33-1, 11, + D# 163 pp 9 F#s: 172 199
34	3 6	Fuel Experimental Data	in Table 3 4 ... "Propylene Oxide" ... "Calculated Energy of Explosion" ...	Section 3.5 2	D# 159 pp # D#125 pp 33-7 Table II F#163 F#206
35	3.7	Fuel Considerations	"The fuels and the necessary figures needed to obtain the total specified warhead energy are listed in Table 3 4."	none	D#125 pp 33-7 Table II
36	3 7	Fuel Considerations	"In real terms diesel fuel, kerosene and gasoline are the same." (regarding combustion chemistry)	none	D#60 pp 6
36	3 7	Fuel Considerations	. "may even be better than the first group (propylene ox de and decane especially)" ...	none	D#188 pp 127 D#125 pp 33-1,7 Table II D# ("#300" pp #, 12 see working copy)
38	4 1	Aerosol Definition and Characteristics	" . the evaporation rate of even higher pressure fluids is too slow for FAE weapons."	none	F# general physics, F#207
39	4 2	Cloud Dispersion	"FAE clouds are usually dispersed by placing a small explosive burster charge along the axis of the cylinder."	none	D#125 pp 33 3
42	4 2	Cloud Dispersion	Table 4 2 .. "Stoichrometric (Detonation) Radii of Fuels"	none	D#125 pp 33-16 Figure 17
52	4 2 3	Cloud Dispersion and Size	"The toroidal case will give a higher peak over pressure over a larger area than the hemispherical case for a fixed quantity of fuel."	none	D#125 pp 33 9/Figure 8

WRAP-UP REPORT

FAE REFERENCE VERIFICATION MATRIX — 28 January 1991

For the wrap-up report, the primary source document is the DSD report ....
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prepared by: Mission Analysis Group, Honeywell DSD

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Page	Section	TOPIC	DISCUSSION	SPECIFIC QUOTED REF	VERIFIED PUBLIC REFERENCE
52	4.2.3	Cloud Dispersion and Size	"For example, one might find substantial 'spikes' superimposed on a hemispherical cloud that are artifacts of the rupture seams in the fuel canister. However it appears from the literature that this may not be a serious problem."	none	D#60 pp 13, 14 F#207
52	4.2.3	Cloud Dispersion and Size	"... average speed is on the order of 80 meters per second." (the piston expansion velocity)	none	F# general physics F#207
54	4.2.3	Cloud Dispersion and Size	"... detonation radius ... Of special interest in this case is decane with a 29% larger rs than diesel fuel."	none	D# ("300" see working copy) F#60
56	4.3	Burster Charge	"The burster charge used for FAE dispersal has been composed of several explosives." ... "TNT, RDX" ... "C-4" ... "The quantity required" ... "generally amounts to three quarters to one percent of the fuel mass."	none	D#125 pp 33-3 Figure 2 D#156 pp 1183
56	4.3	Burster Charge	Figure 4.5 ... "Cloud Radius vs Fuel Density for 80 Meter/Second Average Dispersion Velocity"	none	Not included in the HCSL report F# general physics
57	4.4	Burster Charge	... "typical burster charges driving a dispersive 'gas piston' amount to one percent of the fuel mass and drive the fuel radially outward with an average speed on the order of 80 meters per second."	none	F# general physics (80 meters/sec) D#125 pp 33-18
57	4.4	Burster Charge	"The fuel cloud will also have spikes and other inhomogeneities as artifacts of the war head structure."	none	L#83 D# 60 pp 1
57	4.4	Burster Charge	... "Accordingly, we may conclude that a 1% of fuel mass TNT burster charge will drive the fuel to the stoichiometric radius at which point it can be optimally detonated."	none	D#125 pp 33-18
58	5.1	Aerosol Cloud Detonation - Background	"It is well known ..... detailed investigations ... influence of the tube walls cannot be neglected. ... For small diameter tubes the observed decrease in velocity .... On the other hand, it is also observed .... fails once it emerges ....."	208	H# 70 of 77 entire page is VB from D#208 pp 51 L#83
59	5.1	Aerosol Cloud Detonation - Background	"A possible relation between the spinning detonations in tubes and the detonability limits has been discussed ...."	208	H# 70 of 77 entire page is VB from D#208 pp 52
60	5.1	Aerosol Cloud Detonation - Background	"However, it has been shown that acoustic and non-linear perturbations can be amplified ... "	208	entire page is VB from D#208 pp 53
61	5.1	Aerosol Cloud Detonation - Background	"associated .... detonation wave is not understood."	208	most of page is VB from D#208 pp 53.54
64	5.3	Chemical Detonation	"The possibility exists of chemical detonation of a FAE warhead. Laboratory tests have shown that light FAE hydrocarbon fuels as well as diesel oil can be detonated by the injection of elemental fluorine, chlorine triflouride or bromine triflouride into the aerosol cloud." ... "It is important to note however that this has not yet been achieved with a deployable FAE weapon."	none	D#60 pp 1 D#165 pp 1 D#208 pp 1 H# 32 of 77 H# 37 of 77
65	5.4	Detonation Energy and Delay	"Experiments have established that the average cell size is constant for a self-sustained detonation."	none	F#157
66	5.4	Detonation Energy and Delay	"A rule of thumb that appears successful suggests that a minimum FAE detonation energy is that which is liberated from one or two percent of the fuel weight of TNT."	none	D#125 pp 33-4, 8, 14, 18
66	5.4	Detonation Energy and Delay	... "delay time" ... "is an important parameter whose optimum value can only be determined experimentally."	125	D#158 pp 200 D#60 pp 8 (chemical) D# 208 pp 2, 50 L# 160 pp 200 D#("301" pp 2, 50 see working copy)
66	5.4	Detonation Energy and Delay	"Sedgwick and Krantz (125) are the only published workers in the open literature known to the author to have studied this problem." (delay time) "Elsewhere, delay times for conventional FAE bombs of ... have been reported ... "	125 172	D#125 pp 33-1 + H#s: 18 of 77, 32 of 77, 45 of 77 F#172
68	5.4	Detonation Energy and Delay	"For our case, ..." ... "noting that the average speed (S) of the expanding fuel cloud will be on the order of 80 meters per second." ... "which gives a rough detonation delay range of 0.120 seconds to 0.170 seconds ..."	none	D#125 pp 33-1 Table I F#208 F#172
69	5.4	Detonation Energy and Delay	" ... probable maximum delay times feasible .... propylene oxide beyond 0.180 seconds."	125	D#125 pp 33-7,14 F#208 H#s: 25 of 77, 29 of 77, 31 of 77

For the wrap-up report, the primary
source document is the DSD report ....
entitled: "FAE Warhead Analysis Final Report
dated: December 1984
prepared by: Mission Analysis Group, Honeywell DSD

Symbol Definitions for Verified Public References
D# = verified in report, # referenced in DSD bibliography
H# = verified in abstract, # referenced in HCSL bibliography
F# = not yet verified in report, # referenced in DSD biblio'y
L# = not yet verified in report, # referenced in LATIS list
pp = page number of referenced document
+ = continued on pages following pp
VB = verified verbatim from referenced document

Page	Section	TOPIC	DISCUSSION	SPECIFIC QUOTED REF	VERIFIED PUBLIC REFERENCE
70	5.4	Detonation Energy and Delay	Table 5.1 ... "Variations in Delay Time (Propylene fuel)"	125	VB D#125 pp 33-7 Table
72	5.5	Multiple Clouds & Mutual Detonation	"The detonation transfer experiments involving two FAE clouds were performed for the purpose of determining the maximum allowable space between canisters and the maximum allowable cloud dwell (detonation delay) time. In this first series of experiments, the burster charges of each canister were detonated simultaneously. Each canister comprised 2 gallons of propylene oxide fuel with a length to diameter ratio, l/d, of two. For instance, with a 8.53 m spacing between the canisters and a cloud dwell time of 120 ms the detonation of one cloud did not cause the detonation of the second cloud. ... Table 5.3 "... Experiments"	none	D#125 pp 33-10+, VB pp 33-11 Table IV
73	5.5	Multiple Clouds & Mutual Detonation	" .. another test involved the dissemination and detonation of a seven canister array. ... propylene oxide "	none	D#125 pp 33-14+
74	5.5	Multiple Clouds & Mutual Detonation	Figure 5.3 ... "... detonation transfer experiments ..."	none	VB D#125 pp 33-12/Figure 11
75	5.6	Summary Multiple Clouds	Figure 5.4 ... FAE Clouds .... form a single cloud ... approximately 14 m"	none	VB D#125 pp 33-16/Figure 17
76	5.6	Summary Multiple Clouds	Figure 5.4(duplicate Figure number in DSD report) ... "Burster Delay... P. O. Fuel"	none	VB D#125 pp 33-13/Table V
77	5.6	Summary - detonation charge	"... experience has shown that the detonation charge is more typically about 1% of the fuel mass. This suggests that about 4 kilograms of TNT would be required for the EBD warhead ... Alternative means of detonation using halogen compounds have been achieved in laboratory experiments but are so underdeveloped at this time that a significant developmental program would be required to produce a deployable device."	none	D#125 pp 33-4, 8, 14, 18 F# 209 F# PO, F# Customer-provided specification
77	5.6	Summary - detonation charge	" .. scaling laws suggest that detonation of the EBM warhead could be delayed as long as 0.7 to 0.8 seconds ..."	none	Not included in the HCSL report F# PO, F# Customer-provided specification D#125 pp 33-17
78	6.1	Background - Convent'l vs FAE/Nuclear	Figure 6.1 ... "Qualitative comparison of blast parameters of conventional, nuclear and FAE explosives of similar yield	none	H# 47 of 77, H# 51 of 77 D#142 pp 1, 40 D#188 pp 9 D#190 pp 3, 178+
79	6.1	Background - Convent'l vs FAE/Nuclear	"The most significant difference between conventional high explosives and the others ..... while nuclear and FAE produce peak over pressures over an extended region. Also the Over pressure declines with distance much faster with conventional explosives than with nuclear and FAE."	none	D#190 pp 178+
81	6.2	Scaling Laws	"Full-scale tests have shown this relationship between distance and energy yield to hold for yields over a very large range. Thus, cube root scaling amy be applied with confidence ..."	none	D#125 pp 33-17
82	6.3.1	Model Selection	"This is a reasonable assumption for an experimental situation and may even be approached on occasion with conventional FAE bombs such as the CBU-55B."	none	Not included in the HCSL report F#203, F# 198
82	6.3.1	Model Selection	"In addition, out to the stoichiometric, or detonation radius (rs) the pressure is truncated at 377 newtons per square centimeter to represent the observed pressure within an exploding FAE cloud."	none	Not included in the HCSL report F#203, F# 198
85	6.3.3	Brode Model (Modified)	"The modified Brode model for nuclear blast simulation may be expressed as follows .... and W is in kilotons equivalent yield. It should be pointed out that W in equation 6.3.3 is for an equivalent nuclear detonation. .... However, FAE fuels are k times more energetic than TNT so we get W/2 = kWok, ... This model approximates the FAE case if one truncates the over pressure at 260 psig ..."	160	L#156 pp 93 F# 60 L#'s: 42, 1029, 1130
90	6.5	Blast Summary	"On the basis of this preliminary study, we would suggest assuming a range of f values from 0.05 to 0.5 and carrying out blast calculations and kill probabilities accordingly."	none	Not included in the HCSL report F#'s: 23, 186, 203
91	7.1	Single vs Multiple FAE Canisters	"Detonation of multiple smaller FAE canisters containing a fixed total amount of fuel will cover a greater area with a minimum specified over pressure than can be covered by the detonation of the same amount of fuel in a single large canister."	none	Not included in the HCSL report D#125 pp 33-16 Figure 17
92	7.1	Single vs Multiple FAE Canisters	"An exact analytical expression for C(n) is probably not possible given the practical variables it represents, but it probably looks something like C(n) = f(v)h(B)g(d)u(s)"	none	L#129

#22

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UNCL/ DODCON/ NONINA

Honeywell Aerospace & Defence Ltd.,
12b Alfred Street,
Westbury,
Wiltshire.
BA13 3DY

10th September, 1990

Attention of Mr. Graham Ruthen
Marketing Manager

Dear Graham,

I was very surprised to hear that Honeywell's operation at Corsham had been terminated and of the original complement you were the only person remaining.

Following your discussion with Paul Titchener at the Air Show last week it was not clear how you will operate in future. Obviously if you have to be supported in any System Engineering role from the USA this will involve delays and problems regarding the 'export' of data etc. If on the otherhand you need instant access to UK based Systems Engineering, Charter Aerospace (CAe) would be very pleased to oblige.

We enclose a Capability document for CAe and if we can help in any way please do not hesitate to contact us. Alternatively if Honeywell USA are interested in forming a UK based 'Systems Engineering' organisation CAe would form an excellent base.

Best regards.

Yours sincerely,
for CHARTER AEROSPACE

K. G. SMITH

enc.

FAX TO: HCSL
FAX NO: 0344 446743 PAGE: 1 OF
ATTENTION OF: Colin Miller
FROM: R. ... DATE: 30 Nov
COMPANY: HADL FAX NO:
Post-it Notes from 3M

Read R. Reed
Bookman now

CHARTER AEROSPACE

SYSTEMS ENGINEERING

CAPABILITY / EXPERIENCE

CHARTER AEROSPACE
Charter House
426 Avebury Boulevard
Central Milton Keynes
MK9 2HS

CHARTER AEROSPACE is a privately owned and independent Systems Engineering Company whose activities are totally related to the Defence/Aerospace Industry. The Company was formed in late 1984 with the following objectives :

- Provide Systems Engineering Support to major programs at both National and International level
- Develop "in-house" methodologies and capabilities to secure Aerospace Contracts on a Worldwide basis

The Company's staff are all experienced analysts/engineers having in-depth experience of the Aerospace Industry. Our policy has been to recruit experienced staff to provide an immediate capability in the main disciplines necessary for a successful Systems Engineering Organisation, namely :

- Operational Analysis/Research
- Mathematical Modelling
- Aerodynamics and Flight Dynamics
- Guidance and Control
- Warhead Technology
- Structural Dynamics
- Propulsion

CHARTER AEROSPACE staff have many years experience of working in both National/International environments and are well known in many UK, European and USA Aerospace/Defence Companies.

SYSTEMS ENGINEERING

The study of military systems and concepts in their Operational context provides an invaluable aid to the planning, development and procurement cycle. Techniques can be developed to optimise the Tactical use of In-service equipment as well as quantifying the value of product improvements.

In an era where a high premium is paid for "value for money" cost effective systems, the conduct of System Engineering Studies is an essential part of any military program.

1. The development of techniques and/or methodology with which to assess the system or tactic under consideration. The degree of "realism" or sophistication achieved will depend in the depth to which the problems are to be studied, the ability, experience and resources available to the System Engineers responsible for model development.

2. Models and/or techniques must function within the confines of an Operational Scenario. Typically a scenario would include performance characteristics of all systems to be modelled together with assumptions regarding deployment and behaviour. For example, in the case of Air to Surface systems, terrain and meteorological data would be required to establish intervisibility and target acquisition probabilities.

3. Finally, and most importantly, the conduct of the Study and the presentation of the results must be such as to enable conclusions on the absolute or relative performance of the system or concept to be deduced in an unambiguous manner. It is in this phase of the Study that experienced analysts are seen to the best advantage by clearly demonstrating the cost effectiveness and desirability of the system to the prospective User.

Clearly System Studies are non-trivial pursuits to be undertaken by competent and experienced Engineers/Analysts. The studies should interface/interact with other facets in an attempt to optimise the System

EXPERTISE

CHARTER AEROSPACE staff have participated in many major studies undertaken by UK Industry and Ministry of Defence and many man-years of experience in the assessment of a complete variety of weapon systems and the problems associated with their performance have been accumulated.

Our Engineers translate basic Customer requirements into detailed parameters to allow modelling and subsequent hardware design to proceed. This demands expertise in Mathematics, Physics, Mechanical/Electrical/Control Engineering, Aerodynamics/Flight Dynamics and Computing. Mathematical models of the various sub-systems must be formulated and their interaction studied to produce an "optimum" design giving the required overall performance. Mathematical modelling is central to System Engineering and must accurately reflect actual system performance.

When certain aspects cannot be adequately modelled it is necessary to undertake research efforts to "fill the gaps". By adopting this approach it is possible to translate requirements into detail specifications needed by Design Teams, thus reducing costly "try it and see" policies.

To undertake these tasks all *CHARTER AEROSPACE* Analysts/Engineers have Bachelor or higher level University degrees. Specialists are also available in such fields as Explosives, Aerodynamics, Guidance and Control, Structural Dynamics and Operational Analysis.

An outline of relevant experience is presented in the following paragraphs :

Experienced gained includes:

- Terrain modelling/analysis to predict target detection/acquisition ranges and probabilities
- Weapon System effectiveness against CAS and BI Target Arrays
- Aircraft survivability against current and future AAA/SAM threats

- **Medium Range Air to Surface Missiles**

  Experience gained Includes :

  - Sensor aided acquisition of targets
  - Munition effectiveness analysis ranging from "Dumb" bomblets and Mines to "smart" Anti-Armour Munitions including TGSM's
  - Cost effectiveness evaluation of Aircraft/Missile combinations including attrition studies

- **International Studies**

  CHARTER AEROSPACE staff have gained experience via participation in the following studies:

  - MLRS Terminally Guided Warhead (CDP)
  - Airbase Attack Weapon System Analysis
  - Next Generation Systems for High Value Ships
  - Active/Passive Decoy Systems for Ships

OPERATIONAL ANALYSIS

Mission/Operational Analysis is fundamental to our work and the following are techniques developed "in-house" to support these studies :

- Scenario Development
- Assessment Methodology
- Terrain Modelling
- Simulation Language Development
- Graphics Modelling

CHARTER AEROSPACE staff have, over the past 5 years, undertaken significant research in these particular areas and currently we have an excellent capability equal to any in the UK/European Aerospace Industry.

... ACE offer a significant Operational Analysis capability in the following :

- **Ground Combat**

  Discrete event, stochastic simulation of combat between opposing Armoured Forces with their Anti-Tank Weapons; covering :

  - Main Battle Tanks
  - Anti-Tank Guided Weapons
  - Terrain screening/Line of Sight Analysis/Target Acquisition
  - Weapon Characteristics such as Reaction times, Hit/Kill Probabilities, Firing Rates etc ...
  - In-Service Systems ~ Chieftain, T72/T80 MBT, BMP/Sagger, Milan, TOW etc ...
  - Definition of future System Requirements including Effectiveness and Cost Effectiveness

- **Attack Helicopters**

  - Their role on the modern Battlefields
  - Discrete event simulation models
    - Assessment Survivability/Effectiveness
    - Tactics
    - Weapon Systems
    - Surveillance Tactics/Methods

- **Minefield Modelling**

  - Different Mine Concepts
  - Delivery Methods
  - Lethality/Effectiveness Trade-Offs
  - Synergism from Mines and Covering Fire

- **2nd Echelon Attack Modelling**

  - Simulation of attack by Aircraft/Stand-Off Missiles
  - Aircraft/Missile attrition during missions
  - Availability of C3I Systems/Effects on Missile Launch
  - Missile Sensor Options (Trade-Offs)

- **Counter Air Modelling**

  - Definition of Targets
  - Establish requirements/defeat criteria

    - Area Denial Mines including Disturbance, Self Destruct and Influence Fuzing
    - Cratering/Kinetic Energy Penetrators
- Manned Aircraft
- Stand-Off Missiles - Air/Ground Launched
- Surface to Surface Missiles

AERODYNAMICS/FLIGHT DYNAMICS

The Flight Dynamic requirements necessary to guarantee successful delivery/operation of weapons, demands Aerodynamic Prediction Codes to be readily available. *CHARTER AEROSPACE* staff have many years experience in this field and have developed computer codes for the prediction of missile static and dynamic characteristics over the Mach No range $0.3 \leq M \leq 10$. These codes are applicable to both Canard and Tail controlled configurations and include routines to cater for nose/control surface leading edge blunting, stabilizing flares and boattails.

A complete suite of simulation models has been developed for the assessment of the flight dynamic performance of weapons/munitions. The models available cover the range from the simple point-mass through the Three-Degree of Freedom to the more complex Six-Degree of Freedom models.

WARHEAD TECHNOLOGY

CHARTER AEROSPACE staff have experience in the field of Warhead Technology. This experience covers the modelling/design aspects and although we have no trials facilities arrangements can be made to fabricate and subsequently test warhead hardware.

Expertise can be offered in the following warhead areas :

- Directed Energy
- Blast/Shock
- Fragmentation

Directed Energy warheads refer to those incorporating hollow charge (Munroe) effects in which an explosive charge with a metal-liner cavity is collapsed under intense explosive pressure to form a jet (shaped charge) or a projectile (EFP/SFF). These types of warheads are effective against hard targets such as Tanks, Submarines etc ...

Shock /Blast warheads are effective against relatively thin skinned and low tensile strength structures such as Aircraft, Concrete etc ...

generated from various types of fragmenting warhead, namely :

- Pre-formed (PFF)
- Controlled
- Natural

To support our Warhead activities the DYNA 2D/3D Hydrodynamic codes are installed on our computers. These codes allow high strain rate phenomena associated with shaped charge and explosively formed fragments to be investigated.

Other warhead codes developed "in-house" are available for use in studying, blast, fragmenting and kinetic energy penetrator type warheads.

STRUCTURAL DYNAMICS

The design and analysis of structures is a critical activity and to undertake such studies *CHARTER AEROSPACE* use the MARC/MENTAT Finite Element Models.

MARC is a general finite element code implemented primarily for non-linear analysis, the code deriving its broad applicability by allowing the user access to 4 comprehensive libraries :

- Material Library
- Procedure Library
- Element Library
- Function Library

The user can combine any number of components from each library to provide the "tools" to solve almost any structural analysis problem.

MARC is supported by MENTAT - an interactive finite-element pre and post processing system.

Both MARC and MENTAT are installed on our computers and have been used extensively for analysis of missile structures including random vibration and associated dynamic behaviour.

GUIDANCE AND CONTROL

In the field of Guidance and Control *CHARTER AEROSPACE* has substantial experience and software available for the analysis/design of dynamical systems. Applicable experience covers :

- **Navigation Systems**
    - Development of IN software

- Strap Down IN Systems

- **Guidance Systems**
  - Optimal guidance, control and tracking
  - Non-linear guidance laws
  - Kalman Filters
  - Radar aided mid-course guidance

- **Control Systems**
  - High precision pointing/tracking mechanisms
  - Autopilot design
  - Trajectory shaping
  - Continuous/Discrete frequency and time domain analysis and design

- **System Modelling**
  - Minimum energy central strategy
  - General 6-DOF modelling
  - Adjoint time simulation
  - Rate sensor and accelerometer models

PROPULSION

CHARTER AEROSPACE staff have experience in the field of solid propellant propulsion units including a complete suite of "Design" Computer Codes.

Expertise can be offered in the following areas :

- **Parametric Performance Analysis**
  - Overall propulsion unit configuration
  - Propellant requirement/characteristics
  - Nozzle design
  - Motor design inputs

- Ballistic "trade-off" analysis
- Optimisation of grain design
- Inputs to Thermo-Structural Analysis

- Thermo-Structural Analysis
  - Verification of grain design
  - Compatibility of material stress/strain
  - Propellant structural behaviour

To support the above analyses the following Computer Codes are available on the *CHARTER AEROSPACE* computers :-

1 DF - Mono Dimensional Flow

This code is used for deriving the theoretical motor performance by computing the expansion of the exhaust products through the nozzle assuming 1-D chemical equilibrium and frozen flow.

GRG - Grain Regression

The grain combustion geometry as a function of web and star shape is computed by GRG. A parametric analysis is usually performed by varying the significant geometrical parameters of the star.

BAL - Ballistic Analysis

This code performs the internal ballistic computations of a solid propellant motor by solving the time dependent 1-D gas dynamic flow equations with both heat and mass addition. Variation of grain combustion geometry with time and erosive burning is also considered.

THE - Thermal Analysis

This code performs axisymmetric or planar finite element thermal analysis of orthotropic materials considering spatial co-ordinates and finite differences with time.

STA - Structural Analysis

This code performs finite element analysis of axisymmetric or planar bodies of elastic materials. The code outputs structure deformation and the corresponding stresses/strains.

This is a pre-processor used for mesh generation for input to the *THE* and *STA* codes.

COMPUTING FACILITIES

To support all Technology areas *CHARTER AEROSPACE* have excellent computer facilities. These are shown schematically in Figure 1 and consist of the following units :

- PRIME 4150
- PRIME 2655 (x 2)
- VAX 3600
- HP 1000

Details of the above units including speed, RAM, etc ... are provided in Figure 1.

Graphics capability is provided by Tektronix terminals linked either to the PRIME or VAX systems or running locally connected to a TEK 4170 Graphics Processing Unit. Hard copy output is provided by TEK 4692 and TEK 4695 ink jet plotters.

IBM and TFB RAIR Super Micro computers are also available and can be linked to the PRIME and VAX units.

Office administration and word processing is provided by Olivetti ET350 and two Xerox Documenter Systems (Desk Top Publishing); the latter units being directly linked to the IBM PC systems.

SUMMARY

CHARTER AEROSPACE as a result of extensive investment in resources, software development and computer hardware offer the following :

- Staff to undertake System Design/Development including Engineers, Scientists, Mathematicans - all having an innovative nature.

- Staff fully aware of potential implications whilst exploiting High Technology developments essential in todays competitive environment.

- Acquired experience in Government and Industrial Organisations in areas of Aerospace/Military/Defence in National and International environments.

- *CHARTER AEROSPACE* is dedicated to providing services to the Customer, work is thoroughly documented and prepared to the highest Technical Publications standard.

To obtain further information or a quotation for System Engineering Studies to meet Customer requirements, enquiries should be forwarded to The President, *CHARTER AEROSPACE*. All enquiries will be treated in the strictest confidence and quotations will be provided free of charge.

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PRIVILEGED

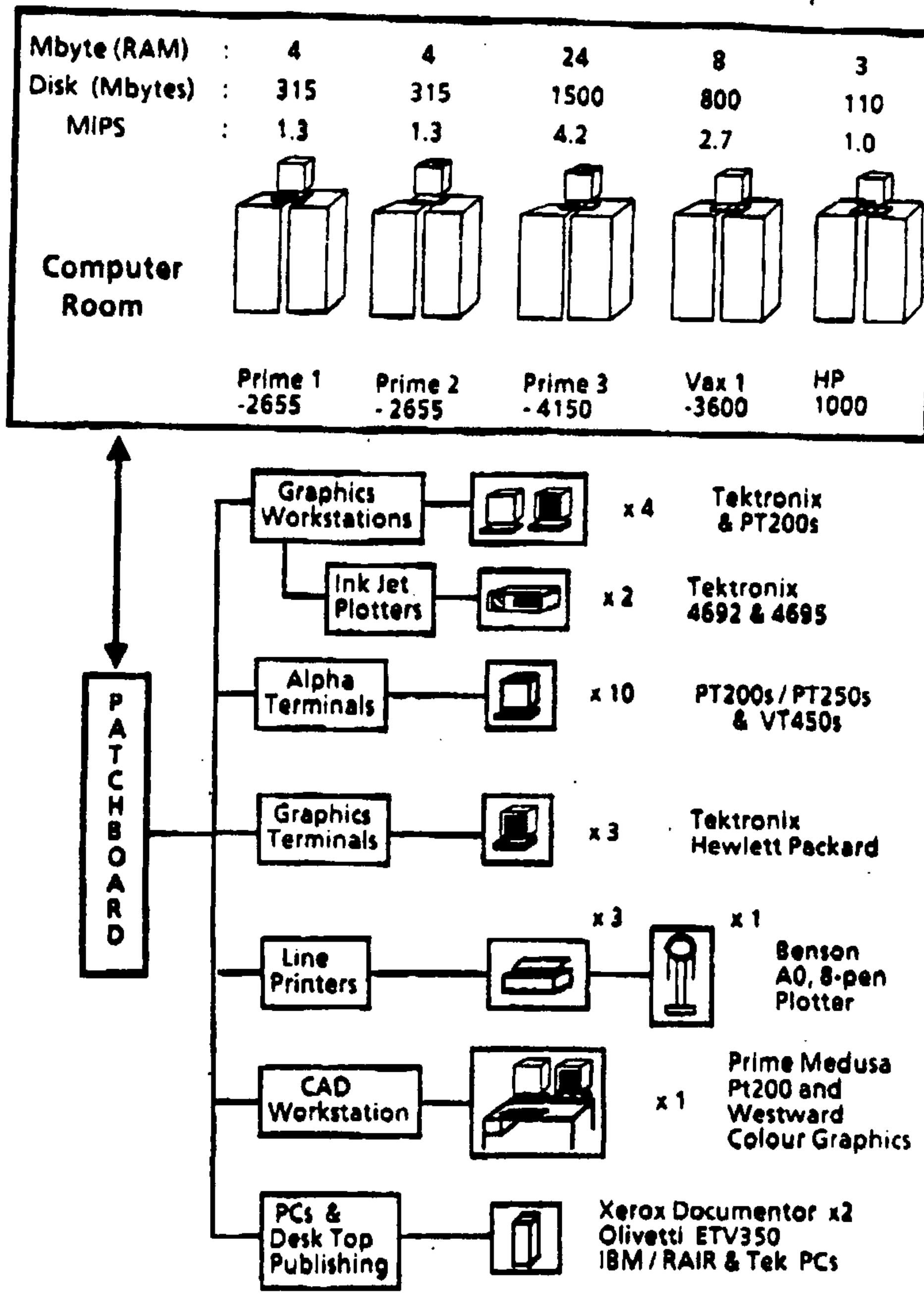

Figure 1 ***CHARTER AEROSPACE COMPUTER FACILITIES***

#23

Privileged and Confidential
Attorney Work Product

REPORT OF INVESTIGATION INTO ALLEGATIONS OF TRANSFER OF HONEYWELL WEAPONS TECHNOLOGY TO IRAQ

COVINGTON & BURLING
1201 Pennsylvania Avenue, N.W.
Washington, D.C. 20044
February 11, 1991

I. Executive Summary

This report sets forth the results of an internal investigation at Honeywell by Covington & Burling into allegations that weapons technology of Honeywell may have been transferred to the Government of Iraq.

A. Transfers to Iraq

The investigation uncovered no evidence of any sale or other transfer of FAE technology of Honeywell to Iraq. We found no evidence of any direct transfer of such technology to Iraq, and no evidence that Honeywell provided FAE technology to any of three sources that have been identified in press reports as having supplied such technology to Iraq: the German company Messerschmidt Bolkow-Blohm GmbH "(MBB"), a Spanish company called Explosivos Alavesas SA ("EXPAL"), or the Chilean arms dealer Carlos Cardoen. We cannot confirm or deny on the basis of the investigation that Iraq received FAE technology from any of those sources.

An Aerospace and Defense ("A&D") unit at Honeywell in Minneapolis and a subsidiary of Honeywell in the United Kingdom, Honeywell Aerospace and Defense Ltd. ("A&D(UK)"), did provide certain FAE studies in 1984 (and possibly early 1985) to a British national, Keith Smith, who represented a Swiss company, the Institute for Advanced Technology ("IFAT"). Smith told Honeywell personnel in 1984, and stated again on interview in the investigation, that IFAT was acting on behalf of the Egyptian government. We conclude the individuals involved at Honeywell reasonably believed in 1984 that the FAE work was destined for Egypt.

Recent press reports have alleged that the FAE report IFAT received from Honeywell was ultimately transferred to Iraq, probably through MBB. We cannot confirm or deny this. We also are not qualified to assess whether such a transfer to Iraq, if one occurred, could materially have aided Iraq to develop and deploy a FAE warhead on a ballistic missile. We have been advised by qualified experts at Honeywell and Alliant Techsystems Inc. ("Alliant") that the FAE study provided to IFAT contained no information or analysis not readily available to any qualified engineer, without access to classified information, and was so elementary that it could not have made any material contribution to the Iraqi FAE capability.

We discovered no evidence in the investigation of any transfer by Honeywell, directly or indirectly, of technology regarding ring laser gyroscopes, cluster bombs, or fuses, either to Iraq or to any intermediary that has been identified as a source of Iraqi weapons or weapons technology.

B. <u>Executive Approval of the IFAT Project</u>

In 1984, Honeywell's Aerospace and Defense International Marketing and Sales Policy No. 54 ("Policy No. 54") prohibited export of "products" constituting "weapons systems" or "weapons components" to customers in Egypt and Iraq (and many other countries), unless an "exception" was approved by the A&D Director of International Marketing at Honeywell, or more senior executives. We have considered whether the non-hardware deliverables involved in the IFAT project -- a report by Honeywell's Defense Systems Division ("DSD") to A&D(UK), and a separate report by A&D(UK) to IFAT -- constituted weapons "products" for purposes of Policy No. 54. Although the matter is not free from doubt, we conclude that they did.

Policy No. 54 did not by its terms require that any particular written or other procedure be followed in consideration of a proposed "exception," although it was standard practice at Honeywell that such a matter was handled in writing. We found no evidence suggesting that any written executive approval of an "exception" under Policy No. 54 was sought for the preparation and transmittal of these two reports to the customers involved. We believe, on balance, that the personnel involved at DSD and A&D(UK) did not follow the standard practice of obtaining executive approval in writing for an "exception" under Policy No. 54.

We believe it would be too speculative to reach a judgment about whether the IFAT project received some form of oral approval from executives responsible for such matters under Policy No. 54. The investigation uncovered some evidence that appropriately senior executives at Honeywell did approve the IFAT project, at least informally and in general terms, at a time when the specific contents of the two reports

4

were not yet known. We believe that personnel at DSD and A&D(UK) who were involved in the IFAT matter believed in good faith in 1984 that the project had been approved by executives authorized to do so under Policy No. 54. Moreover, the investigation revealed no evidence establishing that such approval was denied, or was not sought. On the other hand, there is, in our view, insufficient evidence to conclude that the IFAT project received informal approval from executives at Honeywell responsible for such matters under Policy No. 54.

We found no evidence of any efforts to deceive, nor evidence that senior management at Honeywell directed that the FAE studies be conducted. On the contrary, the proposal to perform an "open" literature FAE study originated with the same personnel at DSD who had opposed other work proposed for A&D(UK) and IFAT on the ground that it would have involved classified information.

C. <u>Exports</u>

DSD prepared and transmitted to A&D(UK) in the United Kingdom in the latter half of 1984, a FAE study ("DSD FAE Report"), at least one draft of the DSD FAE Report, and possibly copies of some source materials used at DSD in the preparation of the report. Smith, as well, received at least some of these materials.

The possible need for an export license was perceived at DSD from the outset of consideration of what became the DSD FAE Report. The individual in DSD's Marketing organization with the authority and responsibility in such international matters was consulted, and he concluded that no export license was required. We believe that he reached this conclusion, in good faith, because the DSD FAE Report was to be conducted solely by reference to unclassified sources in the "open" literature. Honeywell did not apply for an export license for the DSD FAE Report.

We found no irregularities in the manner in which Honeywell concluded not to apply for an export license.

D. <u>Other Matters</u>

Certain checks and balances built into administrative procedures normally followed in the processing of projects at DSD were bypassed in the IFAT matter. We have no reasonable basis to judge whether these procedural matters otherwise affected the processing of the project.

We saw no evidence in the investigation of any bribery, kickbacks, questionable payments, conflicts of interest, or other such improprieties.

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#24

FAE WARHEAD ANALYSIS

FINAL REPORT

DECEMBER 1984

Prepared by

Mission Analysis Group
Honeywell Defense Systems Division
10400 Yellow Circle Drive
Minnetonka, Minnesota 55343

PREFACE

This document, entitled FAE WARHEAD ANALYSIS was prepared for Honeywell Control Systems Ltd. (HCSL) of Bracknell, UK on behalf of the Institute For Advanced Technology (IFAT) of Zug Switzerland who represented the Egyptian Government. The FAE Warhead Analysis was performed under contract (PO) 22/42554/01/Z30 FAE Study/IFAT.

The FAE Warhead Analysis was conducted by L. Lavoie of the Mission Analysis Group within the Honeywell Defense Systems [illegible]. The Mission Analysis Group is located at 10400 Yellow Circle Drive, Minnetonka, Minnesota 55343. Mr. Gareth Thornton of HCSL served as overall project officer.

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1. EXECUTIVE SUMMARY

Nineteen fuels were initially considered as possible FAE fuels. These included several low molecular weight paraffin and aromatic hydrocarbons as well as some alcohols and several common petroleum fuels. Also included were ethylene oxide and propylene oxide because of their demonstrated efficiency as fuel air explosives.

Energies of explosion were calculated where ever possible by computing the reduction in the Helmholtz free energy. In the cases of complex petroleum mixtures like kerosine the heats of combustion were used. Combining these results and other selection criteria such as availability, safety, ease of handling and demonstrated detonability, the list was reduced to twelve promising fuels that met the contractual requirements (see Introduction). These included groups represented by diesel fuels and kerosine, propylene oxide, decane, and benzene.

The process of aerosol cloud formation was examined, and the factors involved in primary and secondary breakup of the main fuel body were presented. The first event burster charge was shown to operate like a fluid piston in pushing the fuel outward where aerodynamic forces ultimately mass stripped the larger droplets producing second and higher order fuel breakup until the droplets reached a detonable size on the order of ten to one thousand microns diameter.

An equation for the stoichiometric radius of the cloud was derived based on the fuel air combustion chemistry. This radius represents the optimum cloud detonation radius. Assuming an average cloud expansion velocity of eighty meters per second gave the minimum second event detonation delay, which was typically 140 to 170 milliseconds. Maximum delays could be as long as seven or eight hundred milliseconds for the system described.

Both the burster and detonation charges were set at one to two percent of the fuel mass.

Several blast models were investigated including those by Kogarko, Sedov, Dow, Strehlow, and Brode. A modified Brode model was finally selected which incorporated a detonation efficiency factor (f). It was felt necessary to make this factor explicit in the blast model because the bursting scenario for the specified system created a situation where cloud homogeneity and stoichiometry could not be assured. Accordingly, the overall blast efficiency might range from less than one percent to more than fifty percent. Other models exist which require elaborate computer codes not available to the author or whose distribution is restricted (the China Lake 'Josephson' model for example). These models were not delt with in the study although the 'Josephson' model is compared here for reference. Blast overpressure vs. radius curves, using the modified Brode model, were presented for each of the dozen fuels.

2. INTRODUCTION

In August 1984 the DSD Mission Analysis group was asked by Honeywell Control Systems Ltd. (HCSL) of Bracknell, UK to undertake a subcontract, Preliminary Study for the Development of a FAE Warhead for Application to a Ballistic Missile. HCSL was to act as the prime contractor on behalf of the Institute For Advanced Technology (IFAT) of Zug, Switzerland who represented the Egyptian government.

DSD's contribution was to provide information for fuel selection in accordance with the contract requirement that potential fuels be among those that are common outputs of a petroleum refinery. In addition, we were to address in a general way the questions of aerosol cloud formation and detonation as well as the blast overpressures one might expect given the fuel and its quantity. Warhead configuration was also briefly treated.

Since the program was ultimately for the Egyptian government there was another contract restraint precluding the use of any classified, restricted, or proprietary materials. While this naturally excluded the best and most important materials we nevertheless were able to prepare a report suggesting the possibilities and problems that would be faced by further work in the area of fuel air explosives (FAE) for delivery by ballistic missile.

The material presented here represents a slightly modified version of the DSD part of the total report. The HCSL part included a literature review (the bibliography of which we have included here), a review of target vulnerability, and an assessment and effectiveness study.

It is worth noting that no where in our study is the issue of blast impulse treated. This was intentional since it was not part of the subcontract work package. This omission should not be construed as a judgement about the importance of impulse. Indeed, no meaningful analysis of an explosive weapons system can be made without a careful treatment of static and dynamic overpressures and impulses, separately and together, as suggested by Abrahamson and Lindberg (175).

3. FUELS

3.1 INTRODUCTION

In accordance with the proposal(1), the requirements for fuel air explosive fuels are that possible fuels for the warhead be available directly from the petroleum refinery and that researched fuels be listed with relevant physical and chemical properties such as density, and energy content. Also, calculations of heat of combustion or explosion are to be made. These requirements are covered in this section.

3.2 FUEL AIR EXPLOSIVE REQUIREMENTS

Fuel air explosive fuels should first be easily obtainable as an output from a petroleum refinery. This can mean ordinary, pure hydrocarbons as well as the more familiar but highly complex mixtures such as petrol (gasoline), kerosine, jet fuel (JP4) and diesel fuel.

It should be a liquid with a high boiling point and low vapor pressure at user temperatures which may reach seventy degrees centigrade. Such properties wll reduce the need for special warhead containers capable of withstanding the positive pressures that would result from a high vapor pressure fuel standing exposed to direct solar radiation.

A FAE fuel should have a high physical density as well as a high chemical energy density. Although there is a nominal net warhead payload limit of three hundred and sixty kilograms, the warhead size and shape define the true fuel quantity limit by virtue of a volume limit. Accordingly, the highest warhead yields would come from the densest fuels. High chemical energy density would come from those compounds with chemical bond breaks yielding the largest energies.

FAE fuels with the highest Helmholtz free-energy decreases for the explosion process are the most desirable. We have chosen, in fact, to find energy yields by computing the Helmholtz free-energy function since it, in principle, more nearly gives us the total theoretical amount of energy transferable from an explosive to the blast wave.

FAE fuels should be non-corrosive and chemically stable for long periods of time for the obvious reasons that systems design and container materials problems will be substantially lessened as well as reducing maintenance costs and increasing system reliability. A potential fuel should also be relatively inexpensive since it might be needed in large quantities.

Ideally, a potential FAE fuel should have a demonstrated ability to detonate. Although there is no way to theoretically predict this property, at the very least it should be flammable.

3.3 FUEL SOURCES

The output of a petroleum refinery is the contractually required source for FAE fuels for this program. Accordingly, the potential list of fuels could go into the tens of thousands. However, for the fuel resource to be readily available we must limit the possibilities to the simplest, lowest molecular weight pariffin hydrocarbons. Some of the simpler olefins, cycloparaffins and arometics might also be considered.

Petroleum refineries are more likely to yield very complex mixtures of hydrocarbon compounds, the most common of which are petrol (gasoline), kerosine, jet fuel (JP4) and diesel fuel. These are all obtainable by 'straight run' fractional distillation of the petroleum crude, and though the base composition of the crude can vary considerably, the typical refinery is capable of tailoring the output to any of the standard fuels just listed. The proportion of petroleum products processed from crude petroleum is given in Figure 3.1. A refinery may also, and often does, produce these fuel mixtures by thermal and catalytic cracking as well as thermal and catalytic reforming.

In addition to possible FAE fuels available from petroleum refineries, we wish to also point out that petrochemical plants are a second and possibly important source of potential FAE fuels.

These plants produce fuels other than hydrocarbons which may include such products as ethylene and propylene oxides, ethanol and methanol. The oxides of ethylene and propylene are of particular interest because of their demonstrated effectiveness in military FAE weapons.

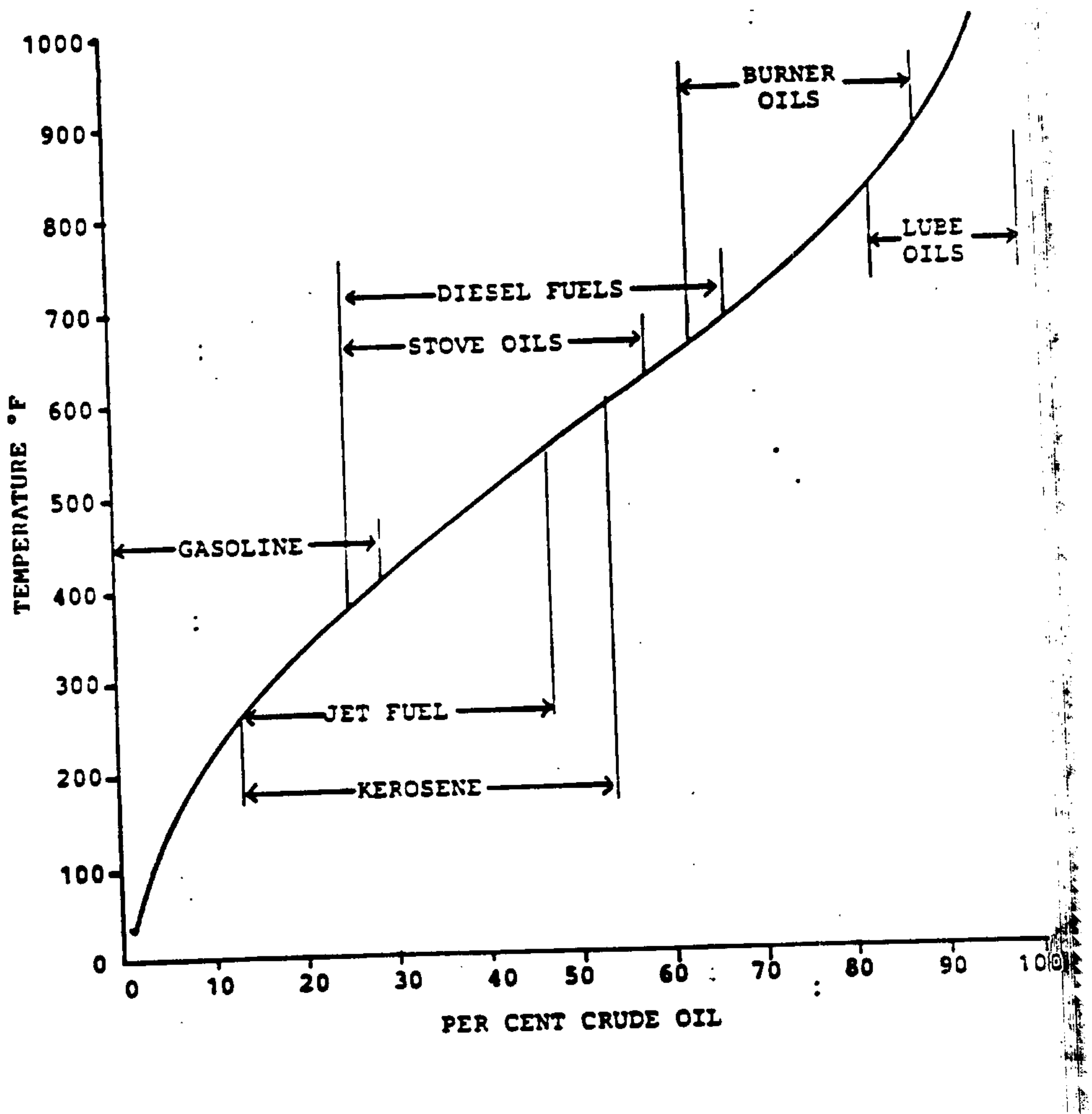


Figure 3.1

Proportion of petroleum products processed from crude petroleum

3.4 PETROLEUM COMPOUNDS AND MIXTURES

Paraffins have the general formula C_nH_{2n+2}, that is, for every carbon atom there are two hydrogen atoms plus an extra two atoms for each molecule. The simplest member of this series is the familiar methane (marsh gas) CH_4. This and the next member, ethane C_2H_6, are gaseous and are normally not present in gasoline.

In the paraffin, the carbon atoms are linked together as a chain. If the chain is straight, the compound is called 'normal,' e.g., n-pentane. If the chain is branched, the paraffin is called iso-, e.g., isopentane. In the higher members of the series, there are a large number of branched arrangements. For example, there are 18 different octanes and 75 different decanes.

Olefins have the general formula C_nH_{2n}. They are chain compounds like the paraffins but differ from them in that somewhere in the molecule, two of the carbon atoms are doubly bonded together, eliminating two hydrogen atoms. Their names are the same as the paraffins except that the suffix -ene is substituted for -ane, e.g., butene, pentene. An older form of the names of the simpler members still sometimes given, uses the suffix -ylene, e.g., butylene.

The double bond in the molecule makes possible a greater number of different arrangements of the carbon and hydrogen atoms, and there are 66 octenes, for example, as compared with 18 octanes.

Cycloparaffins (naphthenes) have the same general formula C_nH_{2n} as the olefins. They differ from the olefins in that they have no double bonds between carbons but instead contain a ring of five or six carbon atoms to which one or more paraffin chains may be attached, e.g., ethyl cyclohexane, C_8H_{16}.

For the general formula, C_8H_{16}, there are four cyclohexanes and four cyclopentanes, or a total of eight cycloparaffins.

Aromatics have the general formula C_nH_{2n-6}. Their molecules contain a characteristic structure known as the benzene ring. This is a ring of six carbon atoms to each of which is attached only one hydrogen. One or more of these hydrogens may be replaced by paraffin chains. The simpler members are benzene C_6H_6, toluene C_7H_8, xylene C_8H_{10}. There are four different xylenes and eight C_9 aromatics.

Gasoline is a mixture consisting almost exclusively of hydrocarbons. There are probably several hundred different hydrocarbons in various proportions in any one gasoline. Most, however, are light paraffins.

Kerosine (approximately 325°F to 575°F boiling range) and wide-cut (approximately 125°F to 575°F boiling range) types of fuels are generally straight-run stocks taken directly from selected crudes by fractional distillation. Kerosine is usually made by a single cut. Wide-cut fuels such as JP4 can be made the same way, or they may be a blend of kerosine boiling fraction plus a lighter stock such as heavy straight-run gasoline or another material in this boiling range. The blend can be pressurized to specification requirements with relatively high vapour pressure materials such as butanes or pentanes as necessary.

Jet fuels made from straight-run stocks consist primarily of paraffinic, naphthenic and aromatic types of hydrocarbons.

Prior to World War II, the aromatic naphthas were produced by the fractional distillation of coal tar and coal-tar residues. These included benzene, toluene and xylene which may be potential FAE fuels. With technical development and the adoption of new processes in petroleum refining, a high portion of these aromatics, plus other types of aromatics not previously available, are now produced by the petroleum industry. In general, however, the aromatics from either source are essentially the same in all respects, with the possible exception of a few specific organic chemical materials originally based on coal tar. The conventional qualities of products from the two sources, such as boiling range, solvency and so on, are the same. In fact, the new processes now used in petroleum refining are producing intermediate- and high-boiling-point types of naphthas that are not available from coal-tar sources.

3.5 FUEL ENERGY CALCULATIONS (206)

The fuel energy available in a FAE explosion may be arrived at in many ways including computing the heat of explosion, computing the energy of explosion, computing or looking up in tables the heat of combustion, or by experiment. We shall illustrate the computational methods using the relatively simple case for a conventional explosive, TNT. The techniques are similar for FAE except for the limitation that the explosion products are not known in detail.

3.5.1 Heat of Explosion

The thermal energy released by the explosive decomposition of a given explosive is in principle easily measured experimentally. The technique is like that for the measurement of the calorific value of a fuel and is as follows:

(1) a small but known amount of explosive is placed in a bomb calorimeter along with an arrangement to initiate its explosion,

(2) a few drops of water are added to ensure complete condensation of any water formed in the products, the bomb calorimeter is purged of air and pressurized with helium (or nitrogen) to avoid combustion effect,

(3) the material is exploded, and

(4) the heat transferred to the calorimeter is measured by noting the temperature rise.

The measured heat value, per unit quantity of explosive, is termed the heat of explosion.

A thermodynamic analysis of the process occurring in the calorimeter during the measurement of the heat of explosion is quite conventional. The products formed are combined within the bomb and are not permitted to perform expansion work, rather they are merely cooled from explosion temperature to calorimeter temperature. The resulting heat flow constitutes the so-called heat of explosion. Also, the thermal capacity of the calorimeter is comparatively great and its net temperature change is small, hence the [illegible] temperatures for the overall process are substantially identical. That is, the process is isothermal. Thus, the heat of explosion corresponds to an isothermal internal energy decrease for the system as a result of the spontaneous explosion, or

$$-\Delta E = \text{heat of explosion} = -(E_2-E_1) \qquad (3.5\text{-}1)$$

where ΔE represents the internal energy of the system, in this case that of some specified quantity of explosive (E_1) or of its products (E_2).

The fact that the products of explosion are not fixed in nature introduces uncertainty into the exact meaning to be attached to the so-called 'heat of explosion' of Eqn. 3.5-1. An experimental measurement with more precise meaning is to be preferred, at least for some purposes. One such definite measurement is that of a heat of combustion. Here the reaction in the calorimeter is caused to be a relatively simple combustion in the presence of excess oxygen supply and the products formed are the result of a complete combustion to carbon dioxide, water and molecular nitrogen. The results obtained then correspond to the basic thermodynamic characteristics of the explosive, and as such do have definite and precise meaning. Using the conventional methods of physical chemistry, these data may be organized and presented in various ways, one convenient way is in the form of values for the internal energy of formation. From the measured values for the internal energy of formation, a heat of explosion may readily be computed for any given products composition, including that which by chance occurs in some particular calorimeter. The computation is illustrated in Example 1, in Section 3.5.4 to follow, where nominal products of explosions are assumed.

The computation of a heat of explosion from these formation data proceeds by first specifying the products to be considered and then finding the internal energy values for these products and for the explosive. The difference in these corresponds to the heat of explosion, as shown in Eqn. 3.5-1. The computation customarily ignores minor items such as the effect of pressure levels, mixing or solution effects and those of non-ideal gas behavior. Required are data on internal energy of formation. These are given in Table 3.1. For a material whose internal energy of formation has not been measured, there are available approximation methods based on group increments and in some instances these may suffice to provide a reasonable estimate. Table 3.2 lists increments for some of the groups of interest in the chemistry of explosives. It should be noted that the group increment approximations in Table 3.2 utilizes the modern sign convention, where decreases in magnitude of a thermodynamic property are considered to b algebraically negative.

3.5.2 Energy of Explosion

The amount of energy transferable from an explosive to a blast wave is a key item in the study of explosions. This flow of energy can be evaluated in terms of gas volume v and pressure P as work of expansion, $\int_{P_1}^{P_2} P dv$, performed by the pent-up gases produced in the explosion, but precise

THERMODYNAMIC PROPERTIES OF PRODUCTS OF EXPLOSION (25°C)

		ΔE_f^o	ΔH_f^o	ΔA_f^o	ΔF_f^o	S^o
O	(g)	58.863	59.159	54.698	54.994	38.4689
O_2	(g)	0.00	0.00	0.00	0.00	49.003
H	(g)	51.793	52.089	48.279	48.575	27.3927
H_2	(g)	0.00	0.00	0.00	0.00	31.211
D	(g)	10.06	10.06	8.93	8.93	43.888
H_2O	(g)	-57.5016	-57.7979	-56.3394	-54.6357	45.106
	(l)	-67.421	-68.317	-56.793	-56.690	16.716
N	(g)	85.272	85.565	81.175	81.471	36.6147
N_2	(g)	0.00	0.00	0.00	0.00	45.767
NO	(g)	21.600	21.600	20.719	20.719	[illegible]
NO_2	(g)	8.387	8.091	12.686	12.390	57.47
NH_3	(g)	-10.45	-11.04	-3.383	-3.976	46.01
C	(g)	171.105	171.698	160.252	160.845	37.7611
(diamond)		0.4352	0.4352	0.6850	0.6850	0.5829
(graphite)		0.00	0.00	0.00	0.00	1.3609
CO	(g)	-26.7220	-26.4157	-33.1042	-32.8079	47.301
CO_2	(g)	-94.0518	-94.0518	-94.2598	-94.2598	51.061
BO	(g)	-5.6	-5.3	-11.9	-11.9	12.91
B_2O_3	(c)	-301.1	-302.00	-282.1	-283.0	12.91
(glass)		-296.7	-297.6	-279.5	-280.4	18.8
HBO_2	(c)	-186.0	-186.9	-169.6	-170.5	11.00
BN	(c)	-32.4	-32.1	-27.5	-27.2	6.00
Al_2O_3	(c)	-389.20	-399.09	-375.88	-376.77	12.186
Na_2O	(c)	-99.1	-99.4	-89.7	-90.0	17.4
Na_2CO_3	(c)	-269.4	-27.3	-249.5	-250.4	32.5
Cl	(g)	28.716	28.012	24.896	25.192	39.4567
Cl_2	(g)	0.00	0.00	0.00	0.00	53.286
HCl	(g)	-22.063	-22.063	-22.769	-22.769	44.617
CCl_4	(l)	-24.9	-25.5	-14.7	-15.3	73.95
$COCl_2$	(g)	-53.0	-53.3	-50.0	-50.3	69.13
F	(g)	18.0	18.3	13.9	14.2	37.917
F_2	(g)	0.00	0.00	0.00	0.00	48.6
ClF	(g)	-13.3	-13.3	-13.6	-13.6	52.05
ClF_3	(g)	-36.4	-37.0	-26.6	-27.2	66.61
HF	(g)	-64.2	-64.2	-64.7	-64.7	41.47
CF_4	(g)	-161.9	-162.5	-151.2	-151.8	62.7
AlF_3	(c)	-311.0	-311.0	-294.0	-294.0	23.0
HF_3	(g)	-265.1	-265.4	-261.0	-261.3	60.70
KCl	(c)	-103.869	-104.175	-98.296	-97.592	19.56
KF	(c)	-134.16	-134.16	-127.12	-127.42	15.91
KHF_2	(c)	-220.28	-210.90	-204.03	-203.73	24.92
K_2O	(c)	-86.1	-86.4	--	--	--
K_2CO_3	(c)	-274.23	-273.93	--	--	--
LiF	(c)	-246.0	-146.3	-139.3	-139.6	8.57
LiCl	(g)	-53.0	-53.0	-58.0	-58.0	51.01
	(c)	-97.4	-97.7	--	--	--

(g) Gaseous; (l) Liquid; (c) Crystalline

ΔE_f^o - Standard internal energy of formation, kilocal per gram mole.

ΔH_f^o - Standard enthalpy of formation, kilocal per gram mole.

ΔA_f^o - Standard Helmholtz free energy of formation, kilocal per gram mole.

ΔF_f^o - Standard Gibbs free energy of formation, kilocal per gram mole.

S^o - The absolute (or third-law) entropy, cal per gram mole per °K.

See "Selected Values of Chemical Thermodynamic Properties." Circular 500, Nat. Bur. of Stds., 1952, for additional items

TABLE 3.1

GROUP INCREMENT APPROXIMATIONS

Group Increment	A	B
substitute $-CH_3$ for $-H$, aliphatic	4	5
aromatic	2	6
remove 2 $-H$ to form double bond	20	0
remove 4 $-H$ to form triple bond	70	-7
substitute $-C_6H_5$ for $-H$	45	17
substitute $-OH$ for H to form an alcohol	-35	0
to form a phenol	-40	1
insertion of -O- linkage to form an ether	-20	0
insertion of -CO-O- to form an ester	-70	5
substitution of -CHO for -H to form an aldehyde	-20	6
substitution of -O for 2 H to form a ketone	-30	1
substitution of -COOH for H to form an acid	-25	6
subsitute $-NH_2$ for H to form an amine	0	0
substitute -CN for $-CH_3$ to form nitrile	35	13
substitute -CI for H	0	6
substitute -S for -O- to form a thioether	35	2
substitute $-NO_2$ for -H, aliphetic	-10	7
aromatic, first	-20	8
aromatic, other than first	0	7
substitute $-NO_2$ for -H of amine, to form nitramine	15	5
substitute $-ONO_2$ for H, to form a nitrate ester	-20	6
for -OH, to form nitrate ester	25	5
add HNO_3 to form nitrate salt of an amine	-70	7
substitute $-HN-NO_2$ for -h to form nitramine	15	5

A = Change in Internal Energy of Formation, kcal/gm mole
B = Change in Entropy

Representative Parent Compounds (25°C and 1 Atmosphere)

Compound		C	D
Normal paraffin hydrocarbons, C_nH_{2n+2}	(liquid)	-9-5.6(n)	25+7.7
	(solid)	-6-6.6(n)	18+5.6
Benzene, C_6H_6	(liquid)	13.5	43.6
	(solid, hypothetical)	11.2	35

C = Internal Energy of Formation
D = Entropy

See G.V. Janz, Estimation of Thermodynamic Properties of Organic Compounds, New York, Academic Press, 1958, for a survey of approximation methods.

TABLE 3.2

evaluation of this line integral can be quite troublesome. It requires a knowledge of the initial pressure generated in the explosion and also the pressure-volume relations for a complex mixture of non-ideal gases whose temperature is changing and whose composition is difficult to establish. Further complexities enter if the process is not adiabatic and appreciable heat losses occur. Such losses, however, are ordinarily minor, except perhaps in underwater explosions where substantial cooling effects may exist.

An alternative to the troublesome evaluation of the line integral above is to make an overall thermodynamic analysis directly in terms of terminal values of pertinent thermodynamic properties. Such as analysis indicates

(1) The maximum energy release that may be obtained in a given explosion is representable as an isothermal decrease in the Helmholtz free-energy function (also referred to as work content).

(2) A change in value for the Helmholtz free-energy function A is a simple difference in point functions A_2 for the explosion products and A_1 for the original materials.

(3) The difference in Helmholtz free-energy represents a limiting or theoretical value and any actual explosive energy release may be less than this.

Discrepancies between the theoretical limiting and the actual explosive energy release can result from the following conditions:

(1) The explosion may be accompanied by some degradation of energy (that is, it may not be reversible).

(2) Heat losses may occur so that the gases expand at lesser volume, and

(3) The temperature of the products after their expansion to ambient pressure is not necessarily identical with ambient temperature. Experience has indicated, however, that none of these items is a major factor. Hence, to a fair approximation, the Helmholtz free-energy decrease for the explosion process is an adequate measure of the energy actually available for explosive yield, as well as serving as an index of the maximum amount theoretically available.

The Helmholtz free-energy is, by definition, the algebraic difference between the internal energy and the temperature-entropy product. That is

$$A = E - TS$$

where A is the Helmholtz free-energy function, E the internal energy, T the absolute temperature and S the entropy. Thus

$$\text{Energy of explosion} = \int_{P_1}^{P_2} P dv = -\Delta A = -\Delta E + T\,\Delta S \qquad (3.5\text{-}2)$$

where $-\Delta E$ is the internal energy decrease measured as the heat of explosion and ΔS the entropy growth for the (isothermal) process. The entropy of a store of energy is an index of its unavailability, the greater its entropy the less this energy is available for performing work. All spontaneous processes represent some loss in availability and hence are accompanied by entropy growth. Equation 3.5-2 assumes that during the explosion process the necessary increase in entropy (or loss in availability) is accompanied by a maximum flow of energy into explosion blast.

Let us compare the relative significances of the calorimetrically measured 'heat of explosion' of Eqn. 3.5-1 and of the 'energy of explosion' of Eqn. 3.5-2. It can be seen that the former is solely a thermal item and that it ignores the energy obtainable from expansion of highly compressed gases formed in the explosion. That is, in a calorimeter any energy of expansion is dissipated irreversibly as in a throttling process and quite as in the classic Joule experiment. But in an ordinary explosion the expansion of these gases may contribute appreciably to the energy transferred to the blast wave. Thus, it frequently happens that the aggregate of the kinetic and internal energies in the hydrodynamic field of the blast wave exceeds the energy release which can be measured in the calorimeter. There is a correlation with the items of Eqn. 3.5-2, where the magnitude of the free-energy decrease exceeds that of the internal energy decrease.

The change in the Helmholtz free-energy in an explosion can, in principle, be computed from data such as the free energy of formation of the explosive and that of the products of explosion. Unfortunately, there are almost no such data available for explosives, most of the investigative work in this field having been of a more practical nature such as shooting bullets at samples of the material. In the absence of the needed basic information, approximation methods may be used to provide rough estimates for theoretical explosive performance. These methods are somewhat indirect. They first assume a products composition and then they estimate a corresponding decrease in internal energy and a corresponding growth of entropy in the explosion process. These two separate items are then combined, as in Eqn. 3.5-2.

3.5.3 Entropy of Explosion

The entropy of explosion represents the entropy growth in the transformation from explosive to products. As for the products, when the nature of these is known their entropy is rather simply a weighted assumption of individual values for each species. For a product that conforms to the specification of the ideal gas, the individual entropy per mole, S, is given as

$$S = S^{o} - R\ln p \qquad (3.5\text{-}3)$$

where S^{o} is the standard molar entropy at unit pressure and the specified temperature. Here R is the molar gas constant (1.987 cal/gm-mole, °K) and p represents the partial pressure of the gas (in atmosphere). The term $-R\ln p$ is sometimes identified as an 'entropy of mixing.' For a mixture of ideal gases at a total pressure of P atmospheres, a given component with mole fraction y exhibits a partial pressure p - yP and a molar entropy

$$S = S^{o} - 2.303\ R\log_{10}y - 2.303\ R\log_{10}P \qquad (3.5\text{-}4)$$

where the term to the right drops out if the total pressure is one atmosphere. Table 3.3 provides numerical values for the item $-R \ln y = -2.303\ R \log_{10} y$.

Equations 3.5-3 and 3.5-4 apply only to gaseous components, and assume the ideal gas laws. For components which are solids or liquids, the entropy is relatively unaffected by pressure, hence the individual entropy per mole at any pressure may be taken as being the standard entropy.

For the computation of the theoretical explosive yield it is also necessary to know the entropy of the explosive itself. But the basic properties of many explosives are not readily available and it may become necessary to rely on approximation methods. However, the entropy for most solid materials is not a large item so that for solids an approximation based on the group increments of Table 3.3 may be reasonably acceptable. Alternatively, an approximation may be based on the observation that, very roughly, for many solid organic compounds,

$$S^{o} = 15 + 5n \qquad (3.5\text{-}5)$$

where n is the number of all atoms present except hydrogen and oxygen. (The constant 15 provides for the hydrogen and oxygen components.) The entropy of liquid materials is, in general, greater than that for solids by an amount related to the entropy of fusion. For some purposes it has been assumed that the entropy of a liquid is about 40 percent greater than that for the corresponding solid.

ENTROPY AND FREE ENERGY OF MIXING

Entropy of Mixing. Cal per gram mole - °K, - R ln y, where y represent the mole fraction of an ideal gas, and R the molar gas constant, 1.9871 defined cal per gram mole - °K.

Free Energy of Mixing. Kilocal per gram mole at 25°C, RT ln y, where y is the mole fraction of an ideal gas, R the molar gas constant 0.001987 kilocalories per gram mole - °K, and T the reference temperature of 298.16°K (25°C or 77°F).

y	-R ln y	-RT ln y	y	-R ln y	-RT ln y
.00	---	0.000	.30	2.391	.723
.01	9.145	2.727	.32	2.263	.675
.02	7.769	2.316	.34	2.142	.639
.03	6.963	2.076	.36	2.029	.605
.04	6.392	1.906	.38	1.921	.573
.05	5.949	1.774	.40	1.820	.543
.06	5.589	1.666	.42	1.723	.514
.07	5.282	1.575	.44	1.631	.486
.08	5.016	1.496	.46	1.543	.460
.09	4.782	1.426	.48	1.458	.435
.10	4.573	1.363	.50	1.377	.411
.11	4.383	1.307	.52	1.299	.387
.12	4.211	1.256	.54	1.224	.365
.13	4.052	1.208	.56	1.152	.343
.14	3.904	1.164	.58	1.082	.323
.15	3.767	1.123	.60	1.016	.303
.16	3.639	1.085	.62	0.949	.283
.17	3.519	1.049	.64	0.886	.264
.18	3.405	1.015	.66	0.824	.246
.19	3.298	0.983	.68	0.766	.228
.20	3.196	.953	.70	0.709	.211
.21	3.099	.924	.72	0.652	.194
.22	3.007	.897	.74	0.598	.178
.23	2.919	.870	.76	0.545	.162
.24	2.834	.845	.78	0.493	.147
.25	2.753	.821	.80	0.443	.132
.26	2.675	.796	.85	0.323	.096
.27	2.600	.775	.90	0.207	.062
.28	2.528	.854	.95	0.102	.030
.29	2.458	.733	1.00	0.000	.000

TABLE 3.3

Computations for the theoretical energy of explosion and thus also the theoretical explosive yield, are subsequently illustrated in Examples 3 to 5 in Section 3.5.4. Using the methods outlined, the heat of explosion for TNT computed as being about 649 calories per gram, in reasonable agreement with measured values. The entropy of explosion is computed to be about 385 entropy units per gram mole of TNT. The corresponding $T \Delta S$ term of Eqn. 3.5-2 becomes about (298 x 385/227) = 506 calories per gram. The sum $- \Delta E + T \Delta A = +649 + 506 = 1155$ calories per gram, giving a theoretical (maximum) that is in good agreement with the value 1120 deduced from blast-wave measurements. Not only is the discrepancy between computed and experimental values quite small, it is also in the expected direction.

In computation of a theoretical explosive yield and of a heat of explosion it is convenient to assume the formation of liquid water (equivalent to a 'higher heating value' in combustion). The latent heat of vaporization of any water product is thereby included in the ΔE term, as occurs in experimental calorimetric measurements made at room temperature. However, the $T\Delta S$ term of Eqn. 3.5-2 is correspondingly reduced so that the effect of this assumption on the values computed for the overall energy of explosion is quite negligible, for there is a nearly complete compensation between the internal energy and the entropy terms of Eqn. 3.5-2.

The explosive yield calculations indicated above are somewhat indirect, for a composite item is involved. It is quite feasible, however, to organize the required data into a form which permits a more direct computation. This calculation requires values for the Helmholtz free-energy function for the explosives and for the products at their partial pressures (rather than at unit pressure). For ideal gases it may be shown that

$$A = A^o + TR\ln p \tag{3.5-6}$$

where A^o is the standard Helmholtz free energy value,

p the partial pressure of a component gas,

R the gas constant, and

T the absolute temperature.

Expressed in terms of its mole fraction y and for a total pressure of P atmospheres, this becomes, for ideal gases

$$A = A^o + 2.303\ RT\log_{10}y + 2.303\ RT\log_{10}P$$

These equations make it possible to find the effect of mixing on the Helmholtz free-energy for each component of an ideal gas mixture (Table 3.3). The energy of explosion can then be computed directly, provided the properties of the explosive and the nature of its products of explosion are known.

Equation 3.5-6, when combined with Eqn. 3.5-2, also permits a calculation of the limiting amount of energy available from the explosive expansion of a store of compressed gas. Assuming n moles of ideal gases and no chemical or nuclear transformation, then for the idealized limiting situation of isothermal expansion

$$\text{Energy of Explosion} = \int_{P_1}^{P_2} Pdv \simeq T\Delta S = nRT\ln(P_1/P_2) \qquad (3.5\text{-}7)$$

where T is the absolute temperature,

P_1 the original (absolute) pressure of the compressed gas and

P_2 the final or atmospheric pressure.

This equation affords a simple means for estimating an approximate TNT equivalent of an explosion due, for example, to the sudden failure of gas tank (see Ex. 5). Equation 3.5-7 involving the molar or universal value of the gas constant R indicates that this explosive energy release depends on the number of moles of gas rather than on the mass. For the many situations in which the various assumptions of isothermal expansion, ideal gases, etc., are not appropriate, evaluation of the internal of Equations 3.5-2 or 3.5-7 may be required. An example is the calculation of the amount of energy released in the explosion of a steam boiler, or by the smokeless powder in a shotgun barrel.

Equation 3.5-7 may be regarded as representing a sort of extreme or limiting situation in which there is no chemical energy release, hence, the E term of Eqn. 3.5-2 is not pertinent. Another limiting situation is an explosion in which a negligible amount of gases are produced, that is, where the $T\Delta S$ term of Eqn. 3.5-2 drops out. This situation is approached in lightning flashes and in nuclear explosions.

3.5.4 Illustrative Examples

Example 1: Compute the theoretical value for the heat of explosion of TNT from its internal energy of formation, assuming a nominal distribution of oxygen in the products of explosion.

The formula for TNT in condensed form is $C_7H_5O_6N_3$, its formula mass is 227 and its internal energy of formation is given as -13.0 kilocal/gm-mole. It can be seen that the nominal oxygen distribution in the products of its explosion calls for six moles of carbon monoxide, one atom of solid carbon, etc. A material balance for this assumed decomposition may be written in the form of a chemical equation using chemical formulae in their usually accepted (quantitative) significance. The standard internal energy of formation for each component is written below the formula for each material.

material balance	$C_7H_5O_6N_3$	C +	$6\ CO$ +	$2.5\ H_2$	$1.5\ N_2$
E^o	-13.0	0	-26.722	0	0

The internal energy change for the assumed transformation is the difference in values for the total amount of products components and for the explosive.

$$\Delta E = (\Delta E^{o})_2 - (\Delta E^{o})_1 = (6 \times -26.722) - (-13.0)$$

$$= -147.3 \text{ kilocal per g-mole.}$$

This internal energy decrease per mole corresponds to a heat of explosion of (147,300/227) = 649 cal per g, which conforms reasonably well with directly measured values.

<u>Example 2</u>: Compute an entropy of explosion for TNT assuming a nominal products of explosion at a total pressure of one atmosphere. The entropy of pure TNT has been measured as about 65 cal per g-mole -°K at 25°C.

The material balance for the assumed decomposition is written in the form of a chemical equation and the entropy for each component ascertained.

material balance	$C_7H_5O_6N_3$	$C + 6\ CO + 2.5\ H_2\ \ 1.5\ N_2$			
S^o	65	1.361	47.301	31.211	45.767
$-R \ln p$	=	=	1.016	2.753	3.767
S	65	1.361	48.317	33.964	49.534

With regard to the individual entropy items, those for the solid TNT and the solid carbon are taken as the standard values. For gaseous components the standard entropy S^o is corrected by adding on the entropy of mixing, as called for by Eqn. 3.5-4, and obtained perhaps from Table 3.3.

The entropy of explosion is the difference in values for the total amount of material for concern.

$$\Delta S = S_2 - S_1 = (1.361 + 6 x 48.317 + 2.5 x 33.964 + 1.5 x 49.534) - 65$$
$$= 385.5 \text{ entropy units}$$

<u>Example 3</u>: Compute a theoretical value for the energy of explosion of TNT using the values obtained above for the heat of explosion and the entropy of explosion.

The internal energy decrease was computed in Ex. 1 as 147.3 kilocal. or 147,300 cal. per g-mole. Combining with the entropy of explosion as computed in Ex. 2, assuming a standard temperature of 25°C (298.16°K) and utilizing Eqn. 3.5-2.

$$\Delta A = \Delta E - T\Delta S = -147,300 - (298 x 385.5) = -262,180 \text{ cal/moles}$$

This decrease in value for the Helmholtz free-energy function corresponds to an explosive energy release of (262,180)/(227), or 1155 cals per g. This theoretical maximum is in good agreement with the observed value of about 1120 cals per g, the discrepancy being at least partially attributable to irreversibilities in the detonation process.

<u>Example 4</u>: Estimate the relative explosive strength of trinitrobenzaldehyde, using approximations based on group increments.

Searching for a 'parent' compound of as similar a structure as possible and for which data are available, a logical choice seems to be TNT. The formula for TNT, $C_6H_2(NO_2)_3$, can be transmuted into that for trinitrobenzaldehyde, $C_6H_2(NO_2)_3CHO$, by the substitution of an aledhyde –CHO group for a methyl $-CH_3$ group.

The internal energy of formation of TNT is given as –13.0 kilocal per gm mole at 250°C and its entropy is known to be about 65 entropy units at that temperature. To transmute TNT into trinitrobenzaldehyde then requires

(1) the substitution of –H for $-CH_3$ in aromatic compounds, and

(2) a substitution of –CHO for –H. By Table 3.3, the internal energy of formation for trinitrobenzaldehyde is estimated as –13.0–(+2)+(–20) = 35 kilocal per g mole. Likewise its entropy is estimated as 65–6+6–65 entropy units.

Computation of the theoretical energy of explosion from these proceeds as in Ex. 1, 2 and 3 above.

Example 5: Compute the explosive energy available and its TNT equivalent from the compressed air in a tank of 2.00 cu ft capacity if at 3000 psia. Assume ideal gas behavior and a temperature of 25°C (298°K).

To use Eqn. 3.5-7 and obtain values in calories, it is convenient to express R as 1.987 cal per g-mole-°K. For this purpose the mass of air must be converted into terms of gram moles.

$$\text{number of lb-moles of air} = \frac{2 \times (3000/14.7) \times (273/298)}{359} \doteq 1.04$$

where 359 represents the number of cu ft per lb-mole of ideal gas at standard pressure of 1 atmosphere and temperature of 0°C. This corresponds to 1.04 x 454, or 473 g-moles of air. By Eqn. 3.5-7,

$$-\Delta A = 564 \times 1.987 \times 298 \ln(3000/14.7) \doteq 1,490,000 \text{ cal total.}$$

This is the equivalent of 1.49×10^{-3} defined tons of TNT, or about 3.3lb.

SYMBOLS

A = Helmholtz free energy, E - TS

°C = Centigrade (Celsius) temperature

E = Internal energy per mole

°K = Kelvin (absolute Centigrade) temperature, C +273.16

m = Mass of an object

n = A number

P = Absolute pressure

p = Partial pressure of a gas component

R = Gas law content (1.98719 defined cal per g mole -°K)

S = Entropy per mole

T = Absolute temperature

v = Volume

W = Explosive energy release, expressed as pounds of TNT

y = Mole fraction of a gas component

Δ = (Delta) a small incremental unit

superscript

o = Indicates standard value at unit pressure

subscript

f = Indicates formation value

1 = Indicates initial value

2 = Indicates final value

ln = Natural logarithm to base e

log = Logarithm to base 10

3.6 FUEL EXPERIMENTAL DATA

Although the calculation of FAE explosion energy is straight forward in principle it is very difficult to do with significant accuracy because the reaction products and proportions are not well defined. For example, the explosion (combustion) of cyclohexane may be ideally described by the equation:

$$2\ C_6H_{14} + 19\ O_2 \longrightarrow 12\ CO_2 + 14\ H_2O \qquad (3.6\text{-}1)$$

Calculation of the heat and energy of explosion depends on the reaction products 12 CO_2 and 14 H_2O. On the other hand, an incomplete reaction with numerous intermediate products, some possibly involving oxides of nitrogen as well, may look like this:

$$?C_xH_y + ?O_2 + ?N_2 \longrightarrow ?CO_2 + ?CO + ?H_2O + ?NO + ?NO_2$$

It is remarkable, in fact, that Equation 3.6-1 can give an experimentally verified answer within a factor of ten. Indeed some theoretical literature on the subject incorporates a constant to correct for these realities which ranges from 0.01 to 0.3. This is saying that the experimentally observed case varies from 1% to 30% from the ideal case.

The case is similar for fuel detonability. There exists no theoretical way to predict whether a flammable fuel will detonate or not. The terms burn, deflagrate, explode, detonate, etc., are distinguished by the velocity of the reaction propagating through the fuel. The slowest is burning which can be of the order of a few meters per second while the fastest detonation can be thousands of meters per second. There is some indication in the literature that the more energetic the detonation charge, the more likely a given fuel will detonate.

We have made no exhaustive search of the several thousand possible fuel products of a petroleum refinery. Our initial fuel selection criteria were that they be relatively common products relatively easily handled. The initial list contained 19 fuels, 8 of which have been demonstrated to detonate (Table 3.4 Midterm Report). On further consideration, the list was reduced to 12 fuels, at least 6 of which have been demonstrated to detonate (see Table 3.4 this report). In reducing the Midterm list, we generally rejected those fuels with such a high vapor pressure at normal temperatures that they are gases requiring pressurized containers, or highly unstable or low yield fuels which had little promise compared to the remainder on the list.

The 12 fuels in Table 3.4 are ranked first for demonstrated detonability with the literature references cited.

The second ranking criterion is the explosion energy density, $E(r_s)$, which is the total warhead energy yield (mass or volume limited) divided by the hemispherical volume of the FAE cloud at the mass or volume limited stoichiometric radius (see Section 4.2.3). We choose this as a kind of invariant maximum figure of merit that is relatively independent of many of the unknowns of the combustion chemistry in a real FAE detonation. We stress, however, that $E(r_s)$ is for the ideal case of 100% detonation efficiency (f=1.0, see Section 6.3) which is never reached in practice.

The Table 3.4 formulae for diesel fuel, kerosine, gasoline, and jet fuel are left blank because they are complex mixtures of dozens if not hundreds of hydrocarbons.

Nevertheless, we have made some educated guesses concerning the average molecular weights of these mixtures by referring to Figure 3.1 and noting that the fuel molecular weight is a rough function of its boiling point. In addition, we have made linear interpolations of the molecular weight ranges of known major hydrocarbons in the mixtures. Accordingly, we believe the estimates listed are reasonable although the three figure precision is arbitrary and shouldn't be taken too seriously.

TABLE 3.4. FUEL LIST

	A	B	C	D	E	F	G
FUEL	Formula	Molecular Weight	Density (g/cm^3)	Heat of Combustion (cal/g)	Calculated Energy of Explosion (cal/g)	E($_g$) Explosion Energy Density (cal/cm^3)	Demonstrated Detonability (Ref. #)
1. Diesel Fuel	—	~226	0.84	10,200	—	1.5	60
2. Kerosine	—	~170	0.80	10,200	—	1.4	125, 155, 162
3. Gasoline	—	~114	0.68	10,200	—	1.3	125
4. Propylene Oxide	$CH_3(CHCH_2)O$	58	0.83	7,600	7,900	1.0	159, 163, 172, 199
5. Heptane	C_7H_{16}	100	0.68	11,500	11,200	1.0	125, 155, 162
6. Decane	$C_{10}H_{22}$	142	0.75	11,400	11,300	0.94	147, 155, 162
7. Jet Fuel (JP4)	—	~170	0.78	10,200	—	1.4	Probably Like Kerosine
8. Hexane	C_6H_{14}	86	0.66	11,500	11,00	0.92	—
9. Xylene	C_8H_{10}	106	0.86	10,300	10,000	0.92	—
10. Pentane	C_5H_{12}	72	0.63	11,600	11,100	0.90	—
11. Benzene	C_6H_6	78	0.88	10,100	9,400	0.90	—
12. Toluene	C_7H_8	92	0.87	10,100	9,700	0.90	—
13. TNT	$C_7H_5N_3O_6$	227	1.63	—	1,120	—	—

The Table 3.4 heats of combustion are taken from standard sources (138, 201, 202) while the calculated energies of explosion are in accordance with the technique outlined in Section 3.5.2. No energies of explosion were calculated for the complex hydrocarbon mixtures since their compositions are unknown.

3.7 FUEL CONSIDERATIONS

With a view to obtaining a feel for the merits of various fuels for the warhead of the ballistic missile, the energy of the fuels has been calculated. The fuels considered and the necessary figures needed to obtain the total specified warhead energy are presented in Table 3.4.

The first column in Table 3.4 contains a list of fuels considered.

Columns A, B, and C list the formulae, the molecular weights, and the densities in grams per cubic centimeter.

Column D gives the heat of combustion in calories per gram of various fuels. The heat of combustion represents the energy released by the complete burning of the fuel (see Appendix B).

Column E gives the calculated energy of explosion in calories per gram of each fuel.

Column F gives $\bar{E}(r_s)$ as described in Section 3.6 in calories per cubic centimeter.

Column G gives the references for those fuels known to detonate.

__Summary__

FAE fuel selection through an essentially theoretical process largely free of any experimental verification would be very risky. We have tried wherever possible to base our study on experimentally verified results. That a great deal of theoretical knowledge exists on combustion chemistry is obvious. However, it is equally obvious that the complexities of the chemistry of a FAE fuel cloud explosion are not completely definable analytically. Accordingly, the three significant figure precision of many of the numbers in Table 3.4 are misleading as far as ranking similar fuel candidates is concerned. In real terms, diesel fuel, kerosine, and gasoline are the same. A more realistic ranking might put the dozen fuels in three categories, fuels one through three are good, low risk possibilities, easily obtained and safely handled. Fuels four through seven will also work and may even be better than the first group (propylene oxide and decane especially) but they are less easily obtainable. The remaining fuels, eight through twelve, are interesting possibilities but have yet to demonstrate detonability and should be considered only in the context of a substantial FAE R and D program.

Therefore, we see diesel fuel and kerosine as the most immediately attractive potential FAE fuels given the program at hand.

4. AEROSOL CLOUD FORMATION

4.1 AEROSOL DEFINITION AND CHARACTERISTICS (207)

An aerosol is any solid or liquid particulant suspension in air. A great range of other terms have been used to describe particulate systems in air as well: dust, smoke, fume, haze and mist are all words in common use with somewhat different but related meanings. Dust usually refers to solid particles produced by disintegration processes, while smoke and fume particles are generally smaller and formed from the gas phase. Mists are composed of liquid droplets.

Aerosols are formed either by the conversion of gases to particulate matter or by the disintegration of liquids or solids. They may also result from the resuspension of powdered material or the break-up of agglomerates. Formation from the gas phase tends to produce much finer particles than disintegration processes (except when condensation takes place directly on existing particles). Particles formed directly from the gas are usually smaller than 1μm in diameter.

The lifetime of an undisturbed aerosol cloud is quite long compared to the times of interest to us even though suspension of small particles in gases at high concentrations are unstable as the particles collide and coagulate as a result of the Brownian motion. The time to reduce the particle concentration to one-tenth its original value by coagulation can be calculated from theory. Table 4.1 shows values of this characteristic time as a function of concentration, N_o (the number of drops per cm^3), for the coagulation of a monodisperse aerosol (droplets all same size) with particle diameter d_p = 0.1μm. From the table it is quite evident that the lower the aerosol concentration, the longer it takes to reduce that concentration. This time changes relatively little with particle size for monodisperse systems.

TIME TO REDUCE THE CONCENTRATION N_o, OF A MONODISPERSE AEROSOL TO ONE-TENTH THE ORIGINAL VALUE, N_o(d_p=0.1μm, T=20°C)

$N_o cm^{-3}$	$t_{1/10}$ (approximate)
10^{10}	1.2 sec
10^9	12 sec
10^8	2 min
10^7	20 min
10^6	3.5 hr
10^5	35 hr

Table 4.1

It is sometimes thought that fuel vapors are necessary for the effective detonation of a FAE cloud, but fortunately this is not so, for the evaporation rate of even higher pressure fluids is too slow for FAE weapons. A vapor is a dispersion of the fuel in the atmosphere at the molecular level, whereas aerosol droplets contain innumerable molecules condensed together. Figure 4.1 and 4.2 illustrate typical evaporation times showing that evaporation is not a linear process with time.

Droplet size is determined largely by wind velocity and fuel viscosity (Table 4.2) as illustrated by the typical curves of Figures 4.3 and 4.4.

4.2 CLOUD DISPERSION (208)

FAE clouds are usually dispersed by placing a small explosive burster charge along the axis of the fuel cylinder. The expanding gases from the explosion then push the fuel outward breaking its volume successively into smaller and smaller drops until each individual drop has fuel stripped from it to form microdrops that are detonable. The stripping process develops as waves are developed in the drop.

According to theory the mean droplet size produced by the primary stripping of a liquid is proportional to the two-thirds power of the fluid viscosity (or effective viscosity) for capillary waves and the first power for acceleration waves. The power lies between these values for the combined model, depending on conditions. The viscosity dependence of the mass mean droplet diameter produced by primary breakup also depends on the stripping conditions (relative velocity and fluid viscosity) as well as on the size of the liquid undergoing stripping, but its value can be much smaller than the preceding values (2/3 to 1 power). On the other hand, under conditions that secondary breakup can occur the viscosity dependence of the final (observed) mass mean droplet size appears to be related to the viscosity dependence of the particular waves that control the final breakup.

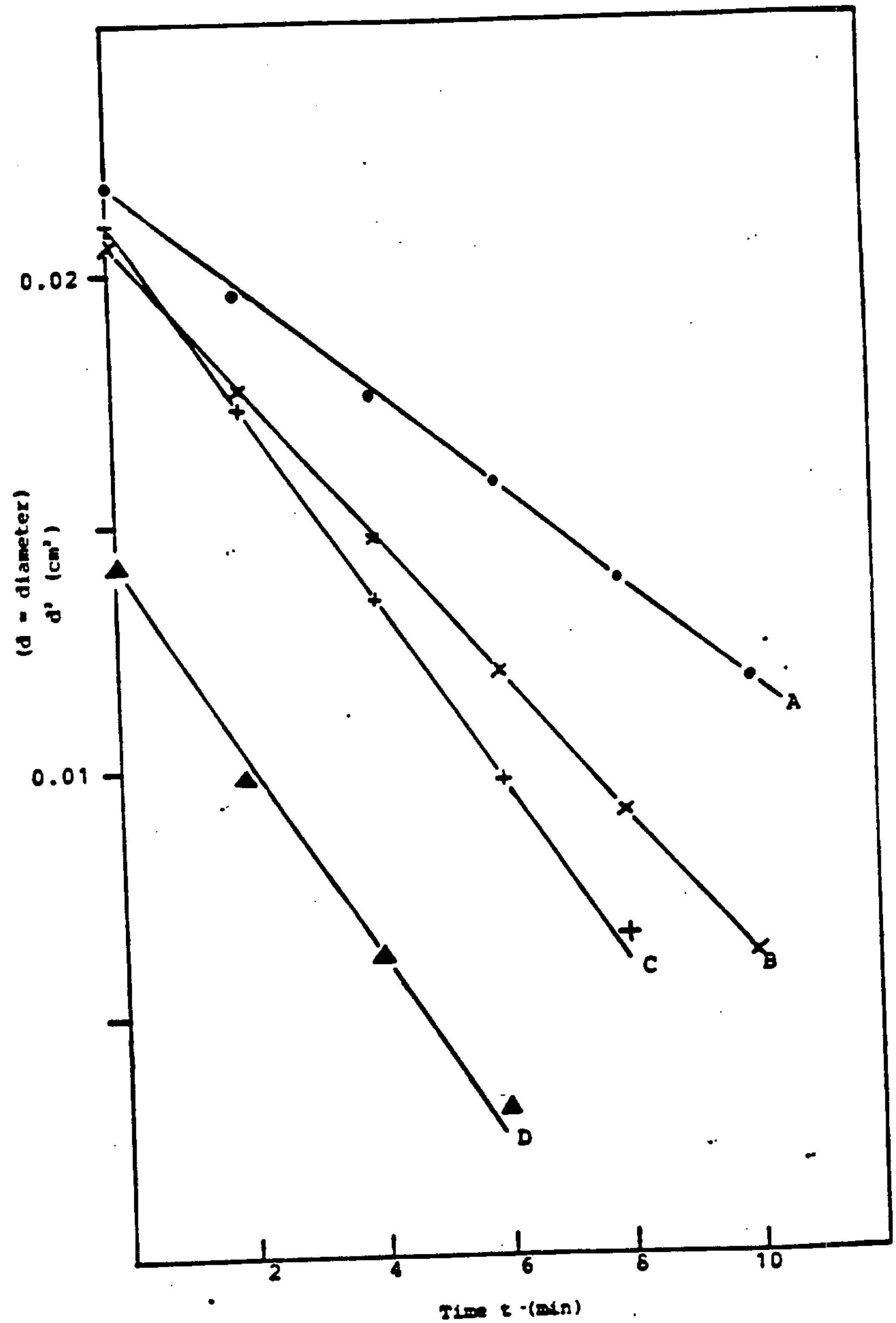


Figure 4.1 Evaporation of drops of furfural in air at 20°C and 1 atm. Air velocity: (cm/sec) (A) 150; (B) 320; (C) 440; (D) 700.

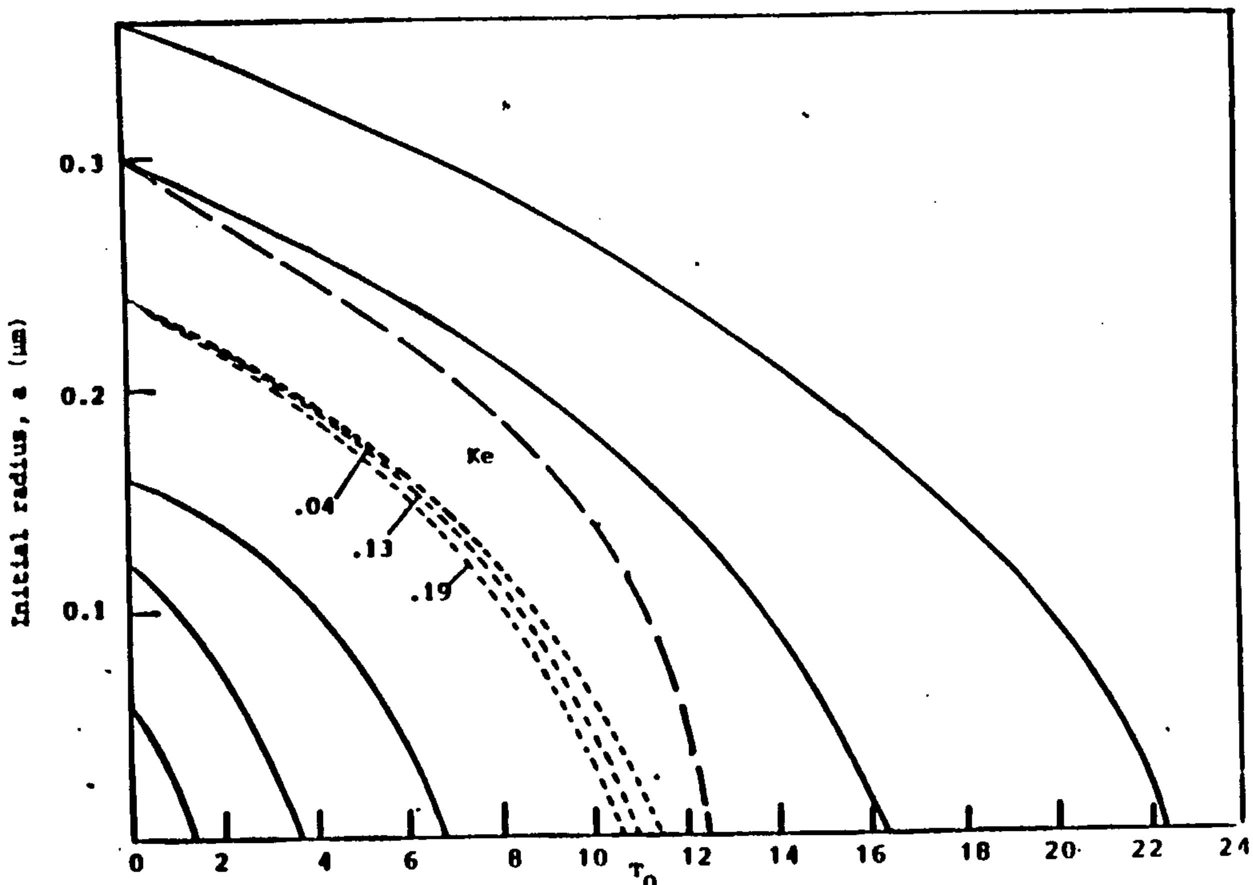
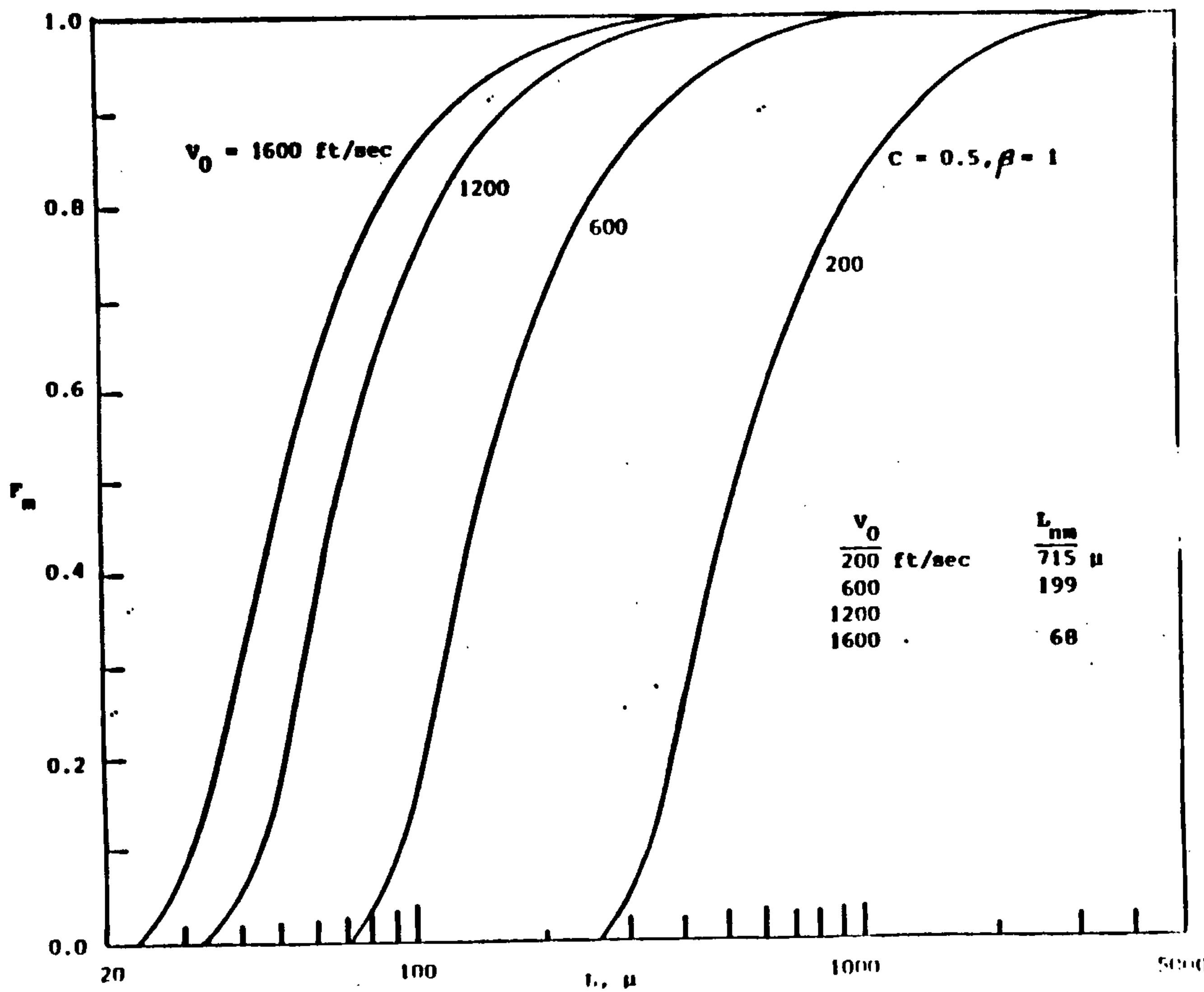


Figure 4.2 Evaporation of fine droplets into vapourfree air at 20 °C and 1 atm., with allowance for Kelvin effect and free molecular flow at surface (Ke=0.1). Initial radii 0.06, 0.12, 0.16, 0.30, 0.36 μm, with allowance for Kelvin effect and free molecular flow at surface (Ke=0.04, 0.13, 0.19). Inital radius 0.24 μm, with allowance for Kelvin effect alone. Diffusion control. Initial radius 0.30 μm.

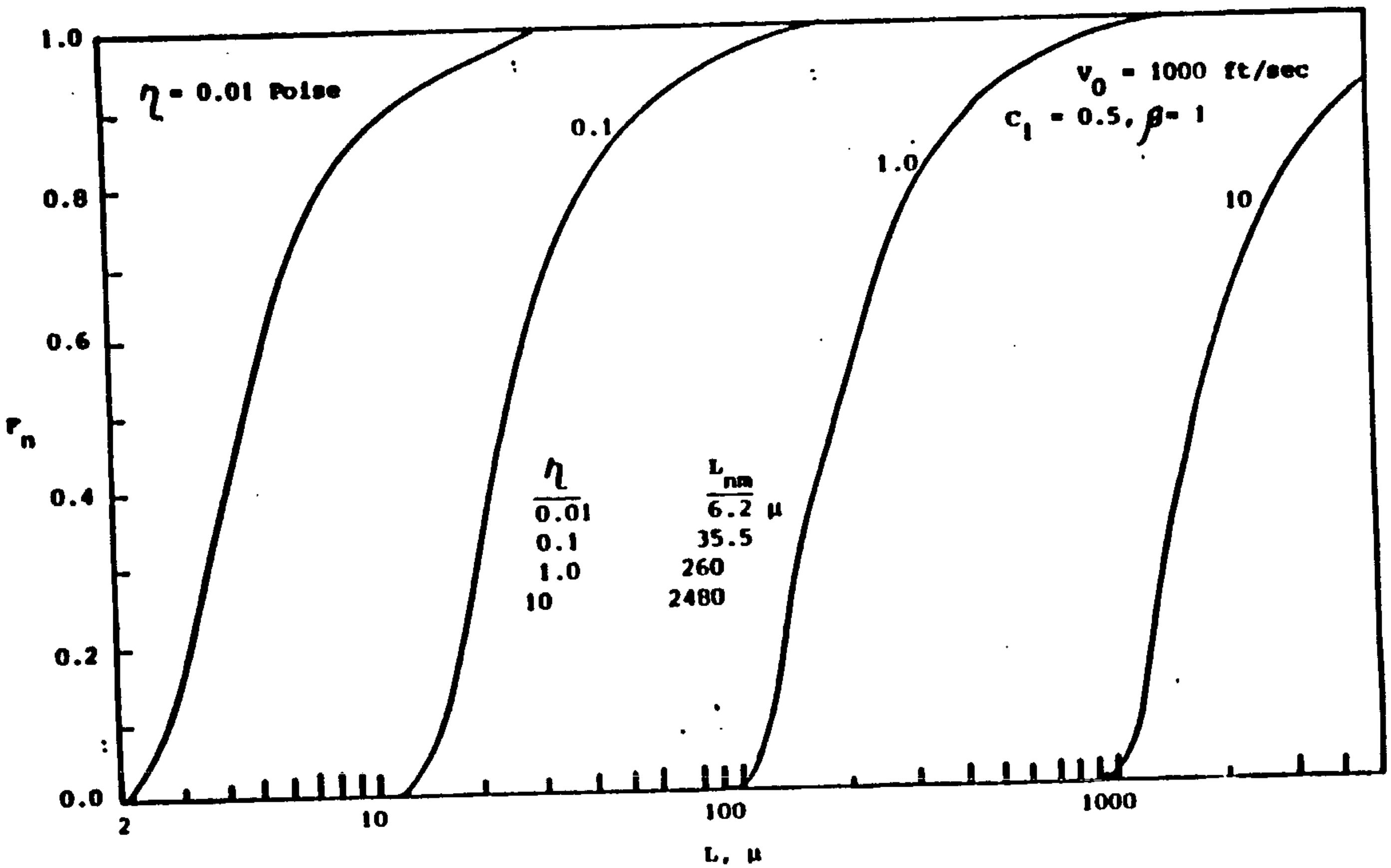
TABLE 4.2. STOICHIOMETRIC (DETONATION) RADII OF FUELS

FUEL	Density (g/cm^3)	Molecular Weight	MASS LIMITED WARHEAD (400 kg) Fuel Mass (kg)	MASS LIMITED WARHEAD (400 kg) Detonation Radius, rs (meters)	VOLUME LIMITED WARHEAD ($0.5m^3$) Fuel Mass (kg)	VOLUME LIMITED WARHEAD ($0.5m^3$) Detonation Radius, rs (meters)	Computed Radius from Fluid Mechanics (meters)	Viscosity at 20°C (Poise g/cm/s)
Diesel Fuel	0.84	~226	400	11.1	420	11.3	12.7	0.001
Kerosine	0.80	~170	400	11.2	400	11.2	12.4	0.0019
Gasoline	0.68	~114	400	11.5	340	10.9	11.5	0.0031
Propylene Oxide	0.83	58	400	11.5	415	11.6	12.7	0.0029
Heptane	0.68	100	400	13.0	340	12.3	11.5	0.0038
Decane	0.75	142	400	13.4	375	13.1	12.0	0.0092
Jet Fuel (JP4)	0.78	~170	400	11.2	390	11.1	12.3	0.0009
Hexane	0.66	86	400	13.4	330	12.6	11.3	0.0033
Xylene	0.86	106	400	13.0	430	13.3	12.9	0.007
Pentane	0.63	72	400	13.5	315	12.4	11.0	0.0024
Benzene	0.88	78	400	12.8	440	13.2	12.3	0.0065
Toluene	0.87	92	400	12.9	435	13.3	13.0	0.0059
TNT	1.63	227	400	0.388+	815	0.492+	—	

+ Radius of a sphere of TNT



1.0
0.8
0.6
0.4
0.2
0.0
F_m
V_0 = 1600 ft/sec
1200
600
200
C = 0.5, β = 1
V_0
200 ft/sec
600
1200
1600
L_{nm}
715 μ
199
68
20
100
1000
5000
L, μ



... on the Number Fraction Distribution

As discussed previously, the primary stripping breakup of a liquid produces a spectrum of particles (drops) whose sizes range from the minimum size, which is determined by wind velocity and fluid viscosity, to the maximum size which is proportional to the linear dimensions of the liquid. A portion of these drops then continue to undergo secondary (and higher order) breakup during their drag deceleration to a stable size.

The drop breakup time depends on the initial diameter D_0 exposed to an aerodynamic flow which causes the drop to undergo surface stripping. The time rate of decrease of the mass of the drop is $(-dm/dt)=(-\rho_1 \pi D^2/2)(dD/dt)$ and this mass loss rate is equal to the wind stripping rate of the drop, i.e., $\dot{M} f_1(\pi D^2/2)$, where the drop is assumed to undergo stripping on some effective fraction, f_1, of its frontal surface area. Since the drop undergoes a certain degree of deformation and spreading during its stripping, the parameter f_1 accounts for the average area that undergoes stripping during the lifetime of the drop in terms of the equivalent sphere frontal area of the drop. Integrating the preceding equation gives the effective equivalent sphere diameter of the drop at any time during its stripping, i.e.,

$$D - D_0 = -f_1 \dot{M} t/\rho_1$$

The time to reduce the diameter to essentially zero size gives the stripping breakup time of the drop, i.e.,

$$t_b = \frac{\rho_1 D_o}{f_1 \dot{M}}$$

4.2.1 Primary Breakup

The mass stripping rate, $\dot{M}$ (g/cm^2 sec), of liquid particles from a cylindrical liquid slug contained on a missile traveling with velocity, V is given by

$$\dot{M} = \frac{K_2\ \rho 1}{L_2 - L_1}\ [\ \frac{f}{a}(B-A) - \frac{fE}{2a^{3/2}} - g\ \ln \frac{L_2}{L_1}\ ] \qquad (4.2\text{-}1)$$

where, $$E = \ln [\ \frac{B + a^{1/2}L_2 + (1/2a^{1/2})}{A + a^{1/2}L_1 + (1/2a^{1/2})}\ ]$$

$$A = (L_1 + a\ L_1^2)^{1/2}$$

$$B = (L_2 + a\ L_2^2)^{1/2}$$

$$f = (\pi/2\rho_1\sigma)^{1/2}\beta\rho V^2$$

$$g = 8\pi^2 C_2 \eta_e^{1/2}/\rho_1$$

$$a = C_1 C_d \rho V^2/4\pi^2\sigma$$

where ρ_1, σ and η_e are the density, surface tension and effective viscosity of the liquid, ρ is air density, K_2, β, C_1 and C_2 are model constants and C_d is the drag coefficient. In the solution of Eqn. 4.2-1, L_1 is considered to be the minimum wavelength, L_{min}, induced on the liquid surface by the aerodynamic wind, which is given by the smallest positive root of the equation:

$$L^3 - a(g/f)^2L - (g/f)^2 = 0$$

L_2 is the maximum wavelength, L_{max}, which is given by

$$L_{max} = eD_o$$

where D_o is the diameter of the liquid and e is a model constant.

In the solution of Eqn. 4.2-1 for a Newtonian fluid, η_e is constant. However, for a non-Newtonian and/or elastic liquid the effective viscosity varies with the shear rate, $\dot{S}$, which is related to the surface stripping rate by

$$\dot{S} = 2/\tau \qquad (4.2\text{-}2)$$

where $$\frac{1}{\tau} = \frac{f}{(L+aL^2)^{1/2}} - \frac{g}{L^2} \qquad (4.2\text{-}3)$$

The solution of Eqn. 4.2-1 should then be carried out on an incremental wavelength basis, using the simultaneous solution of Eqn. 4.2-2 and the experimental relation between η_e and $\dot{S}$ for the fluid in order to obtain the η_e for use in a particular wavelength increment of Eqn. 4.2-1. The effective viscosity is related to the experimental apparent viscosity, η_a, and recoverable shear, s (both of which may depend on the shear rate) by

$$\eta_e = \eta_a(1+s)$$

The consistency of Eqns. 4.2-2 and 4.2-3 with the experimental $\eta_e = f(\dot{S})$ relationship must also be observed in all other calculations involving non-Newtonian and/or elastic fluids.

The droplet stripping rate, $\dot{N}$ (droplets/cm^2 sec), from the liquid cylinder is given by

$$\dot{N} = K_1 (L_2 - L_1)^{-1} \left[\frac{4f}{3}\left[\left(\frac{B}{L_2}\right)^3 - \left(\frac{A}{L_1}\right)^3\right] - 2f\left[\frac{B}{L_2^{\,2}} - \frac{A}{L_1^{\,2}}\right] - \frac{g}{3}\left[\left(\frac{1}{L_1}\right)^3 - \left(\frac{1}{L_2}\right)^3\right]\right]$$

where K_1 is a constant.

The primary droplet size distribution produced by the liquid stripping, based on the cumulative number of droplets, is given for a Newtonian fluid by

$$F_n = \int_{L_{min}}^{L} \dot{N}\, dL \Big/ \int_{min}^{L_{max}} \dot{N}\, dL \qquad (4.2\text{-}4)$$

F_n is the fractional number of droplets having a size between d_{min} (the minimum droplet diameter) and any droplet diameter d, where d is related to wavelength, L by

$$d = FL \qquad (4.2\text{-}5)$$

and F is a constant. For a non-Newtonian fluid the equations must be solved on an incremental wavelength basis. Then

$$F_n = \frac{\sum_{L_{min}}^{L} \int_{L_1}^{L_2} \dot{N}\, dL}{\sum_{L_{min}}^{L_{max}} \int_{L_1}^{L_2} \dot{N}\, dL} \qquad (4.2\text{-}6)$$

The primary droplet size distribution produced by the liquid stripping, based on the cumulative droplet mass, is given by equations similar to Eqns. 4.2-4 and 4.2-5 with F_m replacing F_n and $\dot{M}$ replacing $\dot{N}$, where F_m is the fractional mass of droplets having a size between d_{min} and any d and $\dot{M}$ is given by Eqn. 4.2-1.

The number mean wavelength, L_{nm}, over the entire wavelength distribution, is given by

$$L_{nm} = \frac{2f\,(A/L_1 - B/L_2) - (g/2)\,(L_1^{-2} - L_2^{-2})}{(L_2 - L_1)\dot{N}/K_1} \qquad (4.2\text{-}7)$$

The mass mean wavelength, L_{mm}, is given by

$$L_{mm} = \frac{\rho_l f(BD_m - AC_m + 3E/8a^{5/2}) - \rho_l g\,(L_2 - L_1)}{(L_2 - L_1)\,\dot{M}/K_2} \qquad (4.2\text{-}8)$$

$$C_m = L_1/2a - 3/4a^2$$

$$D_m = L_2/2a - 3/4a^2$$

The number of mean and mass mean droplet diameters are obtained by combining Eqns. 4.2-7 and 4.2-8 with Eqn. 4.2-5.

4.2.2 Secondary Breakup

The secondary (and higher order) breakup calculations begin by partitioning the cumulative mass fraction droplet size distribution (F_m vs d) produced by the primary breakup of the liquid into a number of contiguous zones (about 10) in which all the droplets in each zone are considered as having the same (averaged) properties, size and velocity. The droplet mass in the various zones is then considered to undergo stripping on an incremental time basis, which shifts the mass in the various zones towards zones of smaller droplet diameter according to the stripping rate equation

$$-\Delta_m = \dot{M} f_1 \pi D^2 \Delta t$$

where $\dot{M}$ is given by Eqn. 4.2-1, D is a droplet diameter and f_1 is a constant.

Conservation of mass is maintained over the zones and the number of droplets in each zone is computed from the mass. The change in droplet velocity over a prescribed time increment (while stripping is occurring) is due to drag droplet formation and momentum balance and is given by

$$\Delta V = \Delta V_{drag} + \Delta V_{drop} + \Delta V_{mom.}$$

$$\Delta V_{drag} = \frac{-3C_d \rho V^2}{4 \rho_1 D} \Delta t$$

$$\Delta V_{drop} = -C_3 L \dot{S}$$

$$\Delta V_{mom.} = \sum M_{in} (V_{in} - V)/M$$

where C_3 is a constant and

M_{in} is the mass brought into the zone with velocity, V_{in}.

V is the original zone velocity, and

M is the total zone mass.

The relationship between drop size and detonation rate is shown in Figure 4.5 where it is clear that the smaller the drop size, the higher the detonation rate. (148)

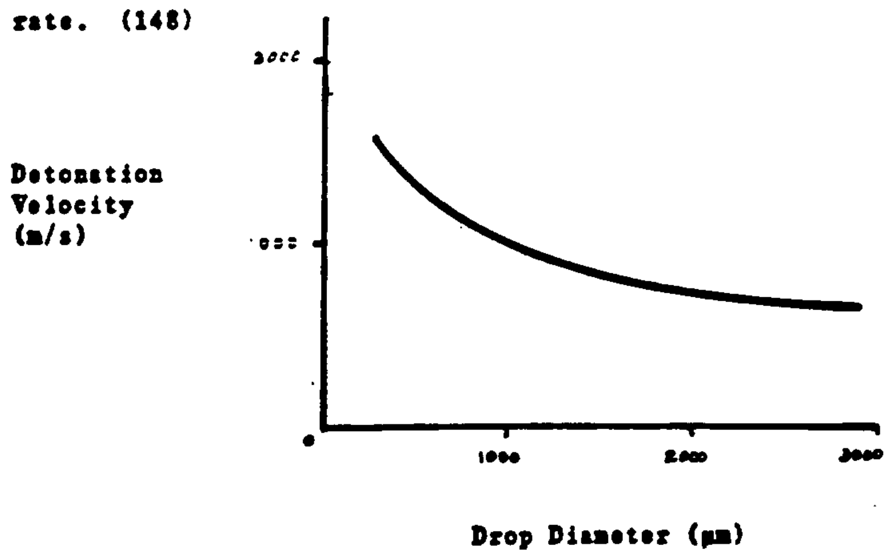


Figure 4.5

4.2.3 Cloud Dispersion and Size

The overall FAE cloud shape can be tailored somewhat to the target requirements. The typical shapes will most likely be hemispherical or toroidal. The toroidal case will give a higher peak overpressure over a larger area than the hemispherical case for a fixed quantity of fuel. It is not clear whether this is due to the obvious geometric advantage or to reinforcement of the blast wave from a horizontally larger source cloud.

The FAE cloud will also have structure related to the nature of the fuel container. For example, one might find substantial 'spikes' superimposed on a hemispherical cloud that are artifacts of the rupture seams in the fuel canister. However, it appears from the literature that this may not be a serious problem.

The ability to compute the cloud radius for a given quantity of fuel is important. Several models exist for this purpose, the most straightfoward using simple geometric considerations.

After the burster charge is detonated, the expanding gases transmit a force through the fuel to the fuel container walls causing them to rupture. The burster gases continue to transmit a high pressure to the fuel which now expands as a coherent mass like a fluid piston. The piston expansion velocity is approximately the speed of sound, 330 meters per second, until aerodynamic drag forces begin to break up the fuel into small droplets whereupon the cloud expansion rate decreases so that the average speed is on the order of 80 meters per second.

The optimum fuel cloud radius will be that which embraces sufficient air to give the proper stoichiometric fuel air mixture. This radius, which we will call the stoichiometric radius, is determined by the quantity of fuel and its combustion chemistry and is unique for each fuel.

We may compute the stoichiometric radius by asking what volume (radius) of air will give the stoichiometric mixture for a particular FAE explosive. We begin by writing the general chemical equation for the fuel combustion

$$A(FAE) + B(O_2) = C(CO_2) + D(H_2O) \qquad (4.2\text{-}9)$$

where A and B are the numbers of moles of fuel and oxygen respectively. (See Appendix A on Fuels for the specific values of A and B for each fuel.)

Given the mass of fuel in kilograms (m_f) or in kilogram moles (m_f/MW_f) where MW_f is the gram molecular weight of the fuel, and the stoichiometrically required mass of oxygen in kilograms (m_o) or in kilogram moles (m_o/MW_o) where MW_o is the gram molecular weight of oxygen, we find from equation (1) that for every mole formula weight of fuel ($m_f/[MW_f\ A]$) we need a mole formula weight of oxygen ($m_o/[MW_o\ B]$)

$$\frac{m_f}{A\ MW_f} = \frac{m_o}{B\ MW_o}$$

or

$$m_o = \frac{B\ MW_o\ m_f}{A\ MW_f} \qquad (4.2\text{-}10)$$

Our original question now becomes, what volume (radius) of air will give us the required mass (m_o) of oxygen. Since volume equals mass divided by density, equation (2) becomes

$$V = \frac{B\, MW_o\, m_f}{\rho_o\, f\, A\, MW_f}$$

where ρ_o is the STP density of oxygen (1.4×10^{-3} g/cm^3) and f is the mole fraction of oxygen in air (.21). Finally, since $V = 2/3\ \pi\ r^3$ for a hemisphere, we have

$$r_s = \left[\frac{3MW_o\, m_f\, B}{2000\pi\, f\, \rho_o\, MW_f\, A} \right]^{1/3} \quad \text{meters}$$

Inserting the numerical values for the constants gives the stoichiometric or detonation radius (r_s) in meters

$$r_s = 3.8 \left[\frac{m_f\, B}{MW_f} \right]^{1/3} \qquad (4.2\text{-}11)$$

Values for r_s are listed in Table 4.1 for mass limited and volume limited warheads. One should note that a ranking of fuels on the basis of detonation radius would lead to a quite different order than the one we have continued from Table 3.4. Of special interest in this case is decane with a 20% larger r_s than diesel fuel.

More elaborate models take into account fuel density, droplet velocity relative to surrounding gas, etc. For example, the final radius (r) (containing most of the liquid mass) of the aerosol cloud that is produced by the stripping of a liquid cylinder is given in one model by

$$r = \frac{1.64\ L\ (\rho_1/\rho)^{1/2}}{1.268 - 8 \times 10^{-4} V + 2 \times 10^{-7} V^2}$$

where V is the fuel speed through the surrounding gas, ρ_1 and ρ are the fuel and air densities respectively, and L is the fuel thickness (approximate warhead radius) in the direction of dispersal. Inserting the values for the EBM warhead of V = 260 feet per second (80 meters per second) and L = 1.15 feet (0.35 meters), which takes into account the burster charge radius, gives

$$r = 0.52(\rho_1/.0014)^{1/2} \quad \text{(meters)} \qquad (4.2\text{-}12)$$

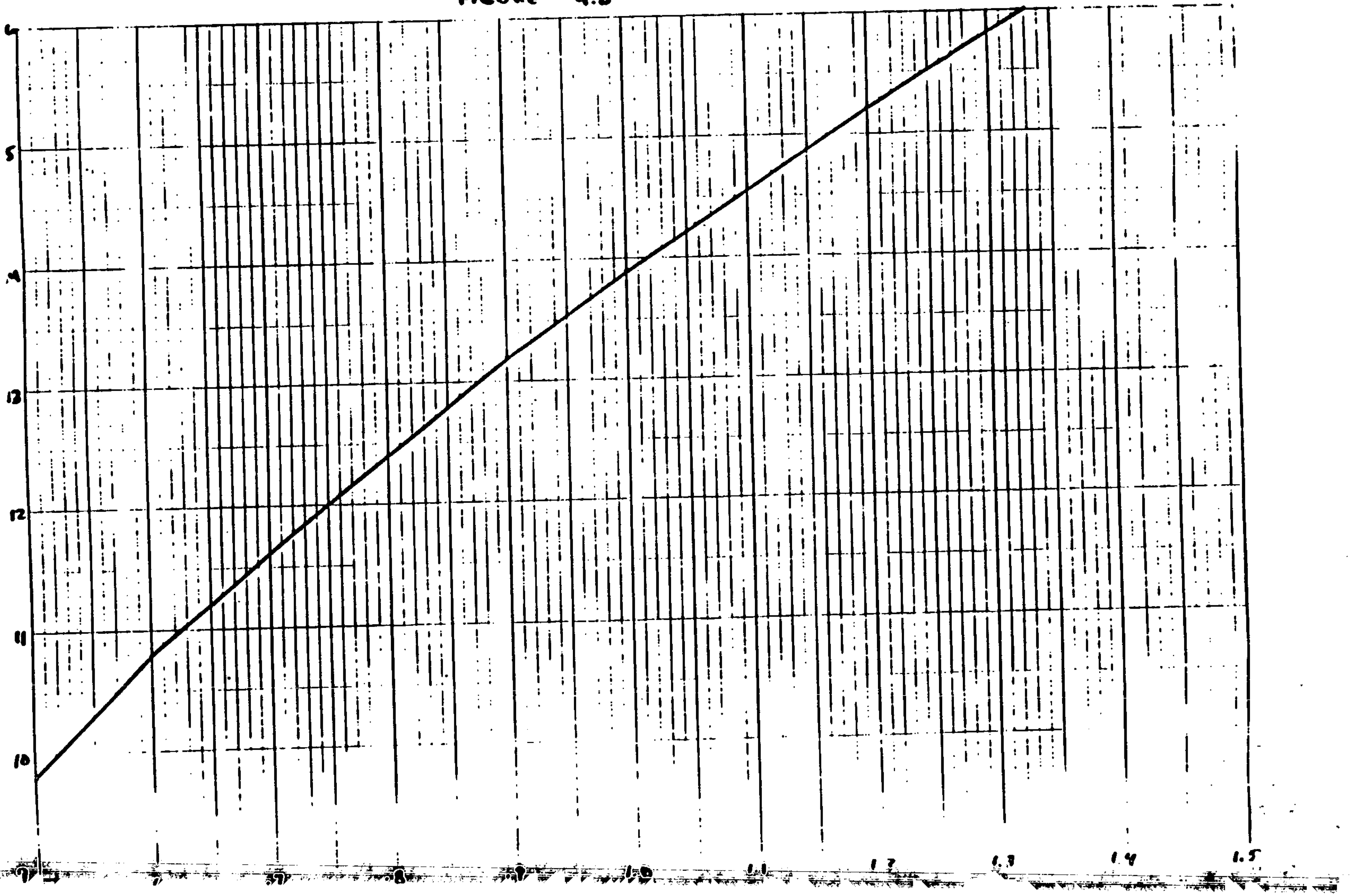
where the density (ρ_1) is in grams per cubic centimeter. Equation (4.2-12) is plotted in Figure 4.6 based on the warhead shown in Appendix C.

4.3 BURSTER CHARGE

The burster charge used for FAE dispersal has been composed of several explosives. The type is not critical, with experiments using TNT, RDX and composition C-4 among others. The quantity required varies somewhat with fuel density and amount but generally amounts to three quarters to one percent of the fuel mass.

CLOUD RADIUS VS FUEL DENSITY FOR 80 METER/SECOND AVERAGE DISPERSION VELOCITY

FIGURE 4.6



4.4 Summary

The calculation of the aerosol cloud formation and droplet size from a moving fuel source, i.e., a source with an air flow around and through it, can be carried out in detail if the suitable experimentally determined parameters are available such as apparent viscosity, and the various model constants. Lacking these, one can still make reliable first order estimates of the FAE cloud size by noting that typical burster charges driving a dispersive 'gas piston' amount to one percent of the fuel mass and drive the fuel radially outward with an average speed on the order of 80 meters per second. The fuel cloud will also have spikes and other inhomogeneities as artifacts of the warhead structure. Simpler models and geometric considerations based on fuel combustion chemistry consistently show dispersion radii between 10.9 and 13.5 meters for the various fuels listed in Table 4.1 if one assumes a hemispherically shaped FAE cloud. Accordingly, we may conclude that a 1% of fuel mass TNT burster charge will drive the fuel to the stoichiometric radius at which point it can be optimally detonated.

5. AEROSOL CLOUD DETONATION

5.1 BACKGROUND (209)

It is now well known that the classical theory of a detonation which regards a detonation wave as a strictly one-dimensional structure consisting of a shock wave followed by a reaction zone is an adequate description of the detonation phenomena. Numerous detailed investigations of the structure of detonations over the past 50 years have shown that the propagation of a detonation is a complex three-dimensional phenomena involving the interactions of finite amplitude transverse waves with the leading shock front, the reaction zone and the boundaries of the system. Although the three-dimensional transverse wave structure of detonation is observed for unconfined detonations, the most detailed investigations of this structure have been done in confined rectangular or round detonation tubes. In these cases, in particular for conditions marginal to the propagation of the detonation wave (i.e., close to the detonability limits), the influence of the tube walls cannot be neglected.

The tube walls have two different effects, namely, an energy and momentum loss associated with the boundary layers and a stabilizing effect on the transverse wave structure. For small diameter tubes the observed decrease in velocity with decreasing tube diameter can be understood in terms of the influence of the boundary layers. On the other hand, it is also observed that an apparently self-sustained detonation in a confined tube fails once it emerges into an area expansion or an unconfined region. For a given mixture there appears to be a minimal critical tube diameter required in order for the detonation to continue to propagate under confined conditions. It has been suggested that this critical tube diameter is related to the characteristic transverse wave of the detonation. In other words, a minimum number of transverse waves is required for a self-sustained detonation in an unconfined situation, thus indicating that the pronounced three-dimensional structure observed in tubes near the detonability limits is stabilized by the confinement provided by the tube walls.

A possible relation between the spinning detonations observed in tubes and the detonability limits has been discussed in the literature where it has been suggested that the condition for stable propagation of a detonation wave in a tube is for the reaction time to be short enough to maintain the spin mode of the lowest frequency in the tube. Thus, if the onset of the single-head spin structure corresponds to a unique fuel composition, the limit could be defined on this basis. Associated with this limit there would then be a characteristic chemical length scale which can be related to the tube diameter and geometry using the acoustic theory of spin detonation. The success of the acoustic theory in predicting the frequency or pitch of the transverse or spinning vibrations observed behind the detonation front further indicates that boundary conditions do play an important role for the propagation of detonations in confined tubes. In fact, according to the acoustic theory, the spin frequencies are entirely determined by the boundary conditions and do not depend on the details of the coupling between the gasdynamics and the chemical kinetics which give rise to the transverse instability in the first place. The only condition being that the reaction time or chemical time be short enough to maintain the spinning mode.

The mechanism by which the tranverse waves are excited and maintained is not completely understood. However, it has been shown that acoustic and non-linear perturbations can be amplified through the coupling with chemical energy release. The amplitudes and wavelengths of the perturbations required to trigger the various instabilities are not known. However, it appears that detonations are unstable to perturbations over a fairly wide range of wavelengths.

The acoustic kenetic interactions depend on the order and the enthalpy of the reaction, the activation energy and most important of all the ratio of the characteristic acoustic time to the chemical time. This is further supported by the stability limits of detonations for various degrees of overdrive assuming a first order Arrhenius rate expression. Although the range of wavelengths over which the detonation is unstable depends on the activation energy and the degree of overdrive, one finds that the detonations are stable only at short wavelengths (i.e., short compared to the length of the reaction zone), and also at long wavelengths for sufficiently large degrees of overdrive.

It appears that transverse waves with wavelengths over a fairly wide range can be excited. Thus the transverse wave structure of a detonation will depend on the preferred transverse mode. This preferred mode will be determined not only by the gasdynamic-chemical kinetic coupling, but also by the boundary conditions (for example, the geometry and diameter of the detonation tube). As long as the characteristic transverse dimensions associated with the boundary conditions are much larger than the characteristic wavelength associated with the chemical kinetics and gasdynamics, the boundary conditions will play a minor role in determining the transverse wave structure. However, for tube diameters of the order of the characteristic transverse wavelength or smaller, the boundary conditions will begin to play a more dominant role, so that for the same mixture the detonation phenomena observed in a small diameter tube could be completely different to that which would be observed in an unconfined situation or in situations with different boundary conditions. Not only could the structure of the detonation wave be different, but composition limits of detonability could also vary with boundary conditions. In fact, it may be possible to trigger 'detonation' phenomena in a tube outside of the limits of detonability for an unconfined situation. The phenomena of 'galloping' detonations may be an example of such a phenomena.

If this is the case and if the onset of the 'galloping' mode is sufficiently precise, then the onset of the 'galloping' mode could also provide a criteria for determining the detonability limits. The 'galloping' mode is a longitudinal mode with periodic destruction and reformation of the detonation where the reformation process is identical to the transition form deflagration to detonation. 'Galloping' detonations can therefore be considered to consist of periodic transitions, in which case the tube walls and confinement are known to play an important role. However, the role of the transverse waves, which are observed in near limit mixtures in maintaining the detonation wave is not understood.

Most fuel-oxygen gas mixtures can be detonated. If a detonating mixture is diluted with an inert gas such as nitrogen, there then exists a particular oxygen to nitrogen ratio below which the mixture can no longer be detonated.

If this oxygen to nitrogen ratio is less than about 0.25 (composition of air), the fuel will also detonate when mixed with air. However, no exact quantitative theory currently exists whereby one can predict, a priori, whether a given fuel-air mixture can detonate, and if so, what the detonability limits are. Neither can one predict whether a flame can accelerate to a detonation in this mixture, or whether the detonation can be initiated directly via a powerful explosive charge.

5.2 EXPLOSIVE DETONATION (210)

Generally speaking, there are two modes of initiation: a slow mode where the detonation is formed via an accelerating flame and a fast mode where the detonation is formed 'instantaneously' when a sufficiently powerful igniter is used. The slow mode is usually referred to as the transition from deflagration to detonation. Turbulence and interactions between pressure waves and flame are the principle flame-acceleration mechanisms that generate the critical states for the onset of detonation. In general, the ignition source plays the dominant role in the fast mode of initiation. The blast wave generated by the igniter energy produces the necessary critical states for the onset of detonation. The fast mode is referred to as direct initiation, since the detonation is formed directly without a predetonation deflagration regime. It is also referred to as blast initiation in some recent literature to emphasize the role that the blast wave plays in the initiation processes. It would be appropriate to call the slow mode of transition from deflagration to detonation self-initiation because the detonation is caused solely by the energy release from the combustion of the mixture itself in the predetonation regime. The parameters that characterize these two modes of initiation are the transition distance for self-initiation and the igniter energy for direct initiation. The basic initiation mechanisms associated with these two modes are understood quite well on a qualitative basis.

Direct or blast initiation is the fast mode in which the detonation is formed in the immediate vicinity of the powerful igniter. The igniter must be capable of not only generating a strong shock wave, but of maintaining the shock above a certain minimum strength for some required duration. For a given igniter, the energy of the igniter characterizes the phenomenon. Below a certain threshold value of the ignition energy, it is found that the blast wave generated by the igniter will progressively decouple from the reaction front. The blast wave decays to a sound wave, and the subsequent propagation of the reaction front is identical to an ordinary flame. This has been referred to as the subcritical regime.

If the ignition energy exceeds the critical threshold value, the blast and reaction front are always coupled in the form of a multiheaded detonation wave that starts at the source and expands at about the Chapman-Jouguet detonation velocity. This is referred to as the supercritical regime.

When the ignition energy is at the critical threshold value, the phenomenon is more interesting. For very early times, the blast and reaction front are coupled. As the blast expands, the decoupling occurs and the reaction front recedes from the shock. However, the decoupling process soon terminates when the chemical energy released by combustion begins to contribute significantly to the blast motion. The blast no longer decays, and the shock wave and the reaction front then propagate as a coupled complex at a constant velocity.

This is called the quasi-steady period of the blast motion, and during this period, the blast strength corresponds approximately to the autoignition limit of the mixture. The duration of the quasi-steady regime corresponds approximately to the induction time at the auto-ignition temperature. The termination of the quasi-steady regime is marked by the sudden appearnace of a localized explosion. However, it is evident that reestablishment is identical to the onset of detonation in self-initiation. In direct initiation, the conditions for the onset of detonation are formed by the reacting blast-wave generated by the igniter. For self-initiation or the transition mode discussed previously, these same critical conditions are derived from the acceleration of the flame itself.

5.3 CHEMICAL DETONATION

The possibility exists of chemical detonation of a FAE warhead. Laboratory studies have shown that light FAE hydrocarbon fuels as well as diesel oil can be detonated by the injection of elemental fluorine, chlorine trifluoride or bromine trifluoride into the aerosol cloud.

This method of detonation has some very attractive advantages over the conventional explosive 'second event' detonation for it eliminates altogether the need for a separate detonation device and synchronization. The detonation is achieved by the 'first event' burster charge which causes the detonating chemical to be injected into the fuel simultaneously with fuel dispersion. It is important to note however that this has not yet been achieved with a deployable FAE weapon.

5.4 DETONATION ENERGY AND DELAY

The explosive detonation energy threshold for FAE clouds is a function of the fuel type and the ratio of fuel to air. A typical comparison of the critical energies for acetylene-oxygen mixtures obtained using various igniters is shown in Figure 5.1. The critical energy versus composition curve demonstrates a characteristic U-shape. The minimum limiting value of the spark energies is generally an order of magnitude less than the exploding wire energies on the basis of the total $CV^2/2$ energy stored in the capacitor.

The dependence of the critical energy on composition is qualitatively the same for most detonating gases. The sharply increasing trends in the initiation energy for fuel-lean and fuel-rich compositions, namely, the vertical arms of the U-shaped curve, are in fact used to determine experimentally the composition limits of detonability of explosive gas mixtures. Accordingly, any point inside of the curve will be a detonation point.

Figure 5.2 illustrates another set of typical detonation energy curves where the most detonable compositions occur at the slightly fuel rich side of the stoichiometric mixture. (Stoichiometry is expressed here as equivalence ratio being the ratio of fuel to oxygen divided by the fuel to oxygen ratio at stoichiometry).

From the above discussions on initiation and limits, one sees qualitatively the narrow limits generally found for unconfined spherical waves as compared to planar waves. Experiments have established that the average cell size is a constant for a self-sustained detonation. Thus, for a planar wave propagating

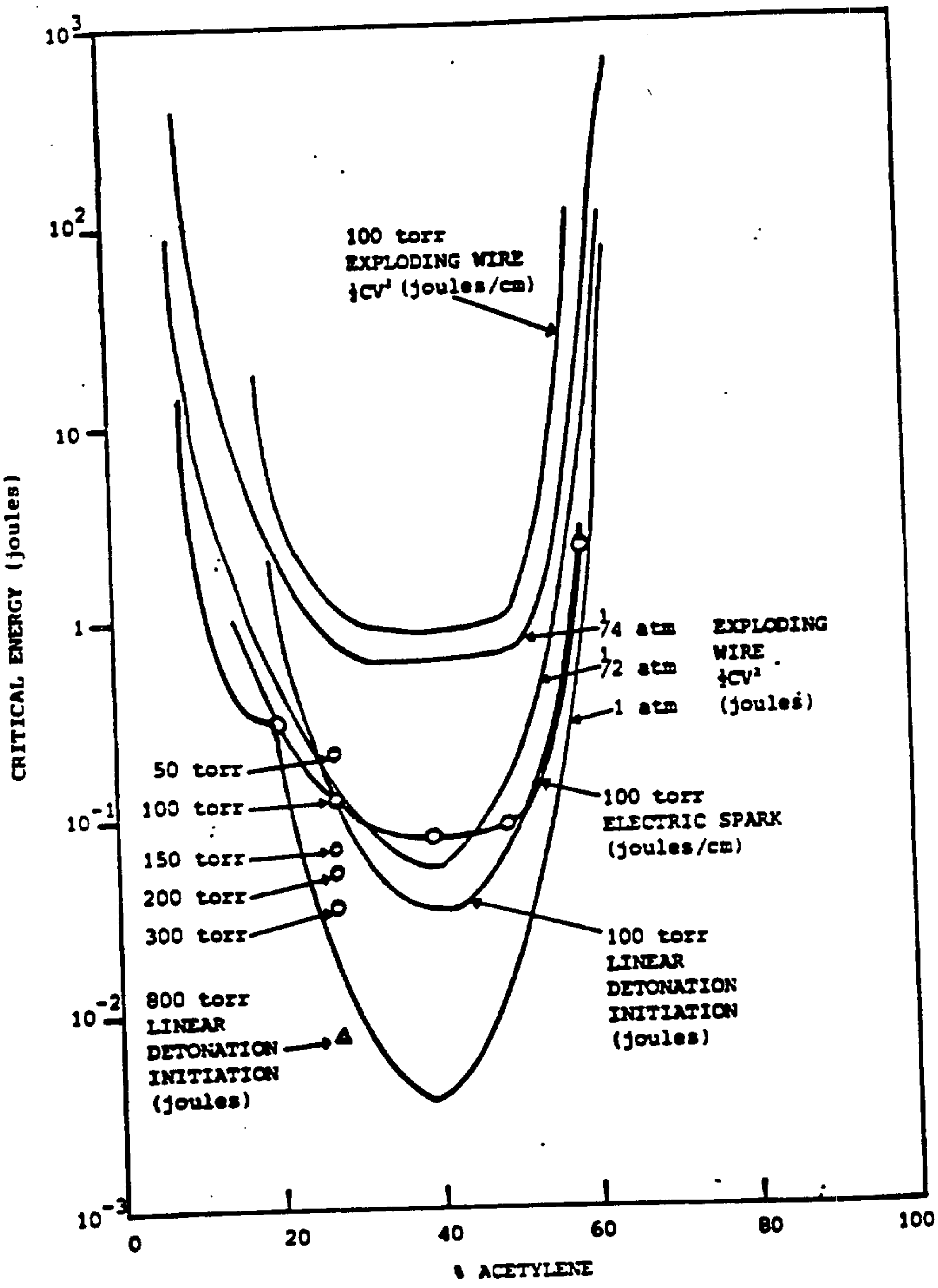


Figure 5.1 The dependence of the critical energy for direct initiation on mixture composition for C_2H_2-

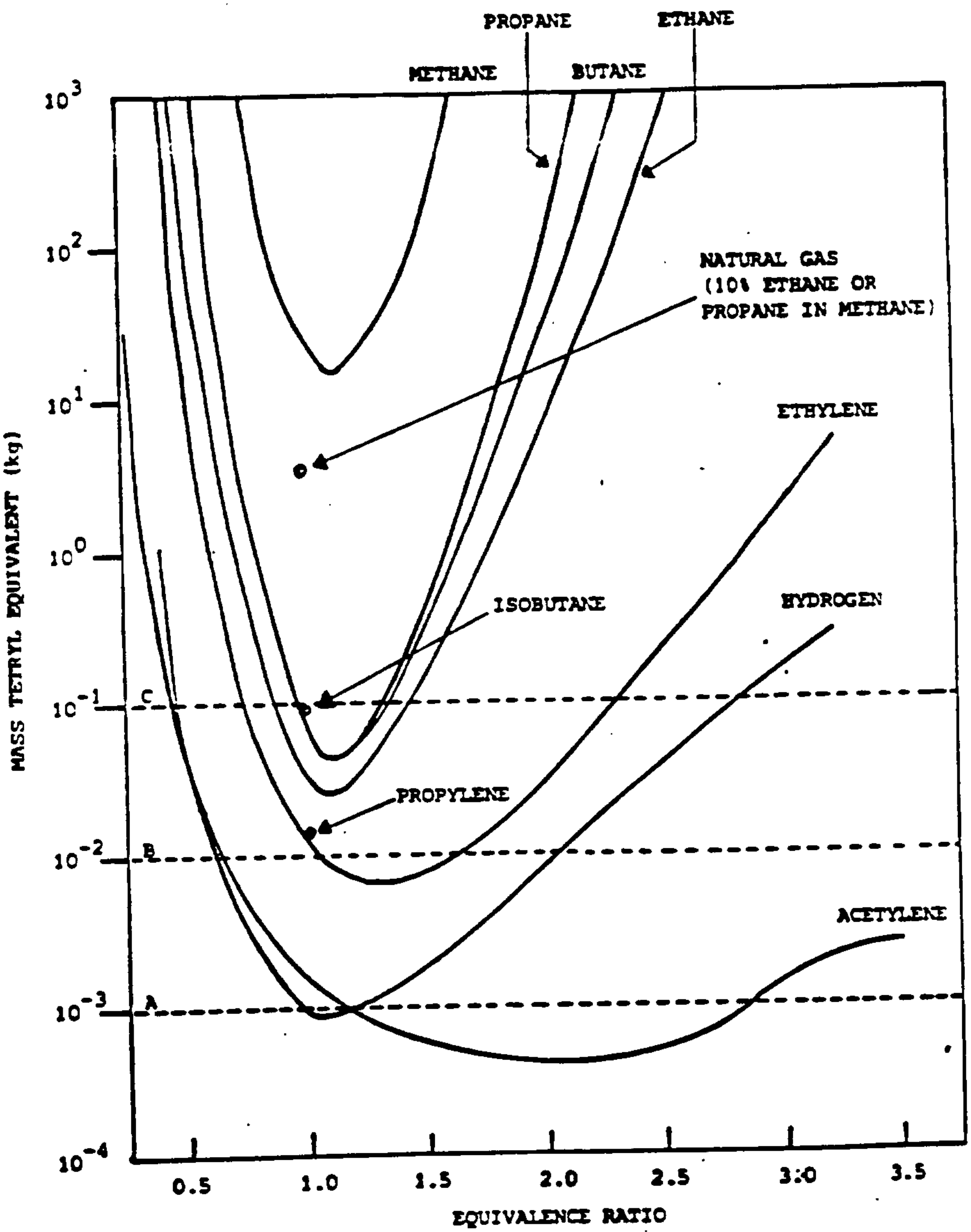


Figure 5.2 Detonability limits versus initiation energy for gaseous fuels in air

in a tube, the total number of cells of the detonation front is, on the average, a constant. However, for diverging waves, the surface area of the front increases with radius. Thus, to keep the average cell dimension the same, the total number of cells have to multiply continuously as the wave expands. This requires the formation of more than one localized explosion at the end of the cycle of a decaying blast wavelet. In this way the cell may divide to form more new cells. If multiplication does not occur in a diverging wave, the cell size gets progressively larger, and the increase in the time for the blast wavelet to decay means that the thermodynamic states at the end of the cycle, when the transverse waves finally collide, may drop below the autoignition limit required for localized explosion to occur. Hence, reinitiation is not possible, and the wave fails. A rule of thumb that appears successful suggests that a minimum FAE detonation energy is that which is liberated from one or two percent of the fuel weight of TNT.

The delay time between the instant the FAE canister is burst dispensing the fuel into an aerosol cloud and the ignition of the fuel detonator is an important parameter whose optimum value can only be determined experimentally.

If the delay is too short, the fuel air mixture will be too rich to detonate (see Section 4.2.3). Also the fuel will not have had time to break up into drops of detonable size. If the delay time is too long, the fuel air mixture will be too lean, while the small drops in the micromist will have coalesced into larger drops which once again will not be detonable. The ease of detonation over the lean/rich range is shown in Figures 5.1 and 5.2.

Sedgwick and Kratz (125) are the only published workers in the open literature known to the author to have studied this problem. The results of their work are summarized in Table 5.1. Elsewhere, delay times for conventional FAE bombs of 227 kilograms and 1136 kilograms have been reported (172) at 0.125 seconds and 4 seconds respectively.

For our case, we can find the approximate detonation delay time (t_d) by noting that the average speed (S) of the expanding fuel cloud will be on the order of 80 meters per second. From equation 4.2-11 of Section 4.2.3 we can get the stoichiometric or detonation radius (r_s). Accordingly,

$$t_d = r_s/S \tag{5.4-1}$$

which gives a rough detonation delay range of 0.120 seconds to 0.170 seconds for the fuels listed in Table 5.2.

Some idea of the probable maximum delay times feasible can be gained by noting that Sedgwick and Kratz (125) could not detonate 6.17 kilograms of propylene oxide beyond 0.180 seconds. Using the following scaling law,

$$t_2 = t_1 \, (W_2/W_1)^{1/3}$$

where t_1 = 0.18 seconds, W_1 = 6.17 kilograms, and W_2 = our mass limited case of 400 kilograms, we get t_2 = 0.723 seconds as the maximum delay time to detonate proplyene oxide. This time probably could be extended by using a higher energy detonator, but there seems to be no reason to do so.

VARIATIONS IN DELAY TIME

(Propylene Oxide Fuel)

Delay Time (ms)	Detonation
40	Yes
60	Yes
120	Yes
180	Yes
210	No
240	No
360	No

TABLE 5.1

5.5 MULTIPLE CLOUDS AND MUTUAL DETONATION

As will be discussed later, there are some advantages in principle to dispersing a fixed weight of FAE fuel among several smaller clouds instead of in one large cloud. On the other hand, one of the problems is to achieve very nearly simultaneous detonation of each of the cloudlet detonators. If this is not achieved, the first FAE explosion may disperse the nearby cloudlets so much that they may no longer be of a detonable fuel air ratio by the time their detonators go off.

TABLE 5.2. FUEL DETONATION DELAY TIMES

FUEL	MASS LIMITED DETONATION DELAY t_d (sec)	VOLUME LIMITED DETONATION DELAY t_d (sec)
Diesel Fuel	0.14	0.14
Kerosine	0.14	0.14
Gasoline	0.14	0.14
Propylene Oxide	0.14	0.15
Heptane	0.16	0.15
Decane	0.17	0.16
Jet Fuel (JP4)	0.14	0.14
Hexane	0.17	0.16
Xylene	0.16	0.17
Pentane	0.17	0.16
Benzene	0.16	0.17
Toluene	0.16	0.17

Although there is little in the liesterature on this subject, one researcher has successfully transferred the detonation of one cloudlet to another thereby avoiding the problem of synchronized multiple detonators.

The detonation transfer experiments involving two FAE clouds were performed for the purpose of determining the maximum allowable spacing between canisters and the maximum allowable cloud dwell (detonation delay) time. In this first series of experiments, the burster charges of each canister were detonated simultaneously. Each canister comprised 2 gallons of propylene oxide fuel with a length to diameter ratio, 1/d, of two. Table 5.3 presents the various experiements performed and indicates whether or not the detonation transferred from one cloud to the other. For instance, with a 8.53m spacing between the canisters and a cloud dwell time of 120ms the detonation of one cloud did not cause the detonation of the second cloud.

DETONATION TRANSFER EXPERIMENTS

(2 gallons, 1/d = 2, P.O. fuel)

Spacings, S (M)	Time Delay (ms)	Cloud-Cloud Detonation Transfer
8.53	120	No
7.32	120	Yes
7.32	120	No
6.72	90	Yes
6.71	160	Yes
7.92	160	No
7.32	160	Yes

TABLE 5.3

Representing the results of this set of experiments graphically, as in Figure 5.3, shows clearly that as the spacing between canisters is increased more time for cloud dispersal must be allowed to ensure a successful cloud to cloud detonation transfer. Consequently for successful detonation transfer, cloudlet overlap is a requirement.

Following on from this research work another test involved the dissemination and detonation of a seven canister array. Each canister contained 3.18 kg (7 lbs) of propylene oxide. The length to diameter ratio, 1/d, of each of the canisters was 2 and the fuel to burster ratio, F/B was 100. The canisters were placed in an array as shown in Figure 5.4 In this test the cloud dwell time was 100 msec and t was 0, i.e., the burster charges in all of the containers were detonated simultaneously. Second event detonators were placed in only one of the clouds so that the ability of the detonation to transfer in this configuration could be determined. The results showed that detonation did indeed transfer throughout the multicloud array.

Table 5.4 shows the effect of lack of fuel dispersion simultaneity on detonation transfer efficiency. Not surprisingly when one of the cloudlets is old compared to the other there is less likelihood that the detonation will transfer.

5.6 SUMMARY

The only way to determine whether a given fuel will detonate in air is to experimentally test it since no predictive theory exists. We have ranked the fuels listed in Table 5.2 primarily by their experimentally demonstrated detonability. Diesel fuel, kerosine, gasoline, propylene oxide, heptane,

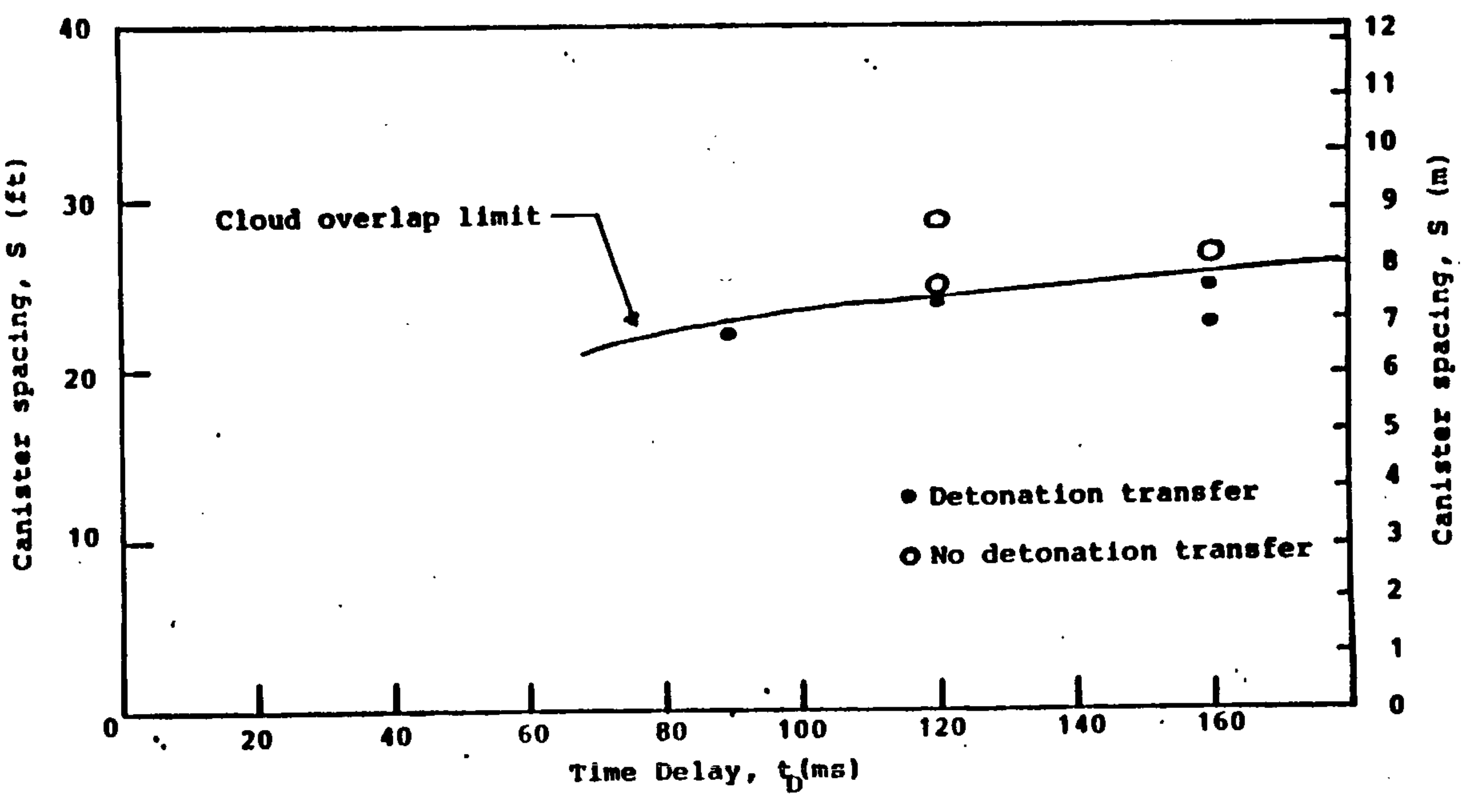


Figure 5.3 Results of detonation transfer experiments. Spacing, S, between canisters versus delay time, t_D, between burster initiation and cloud detonation. Propylene oxide fuel, 2 gallons, l/d = 2, F/B = 90.

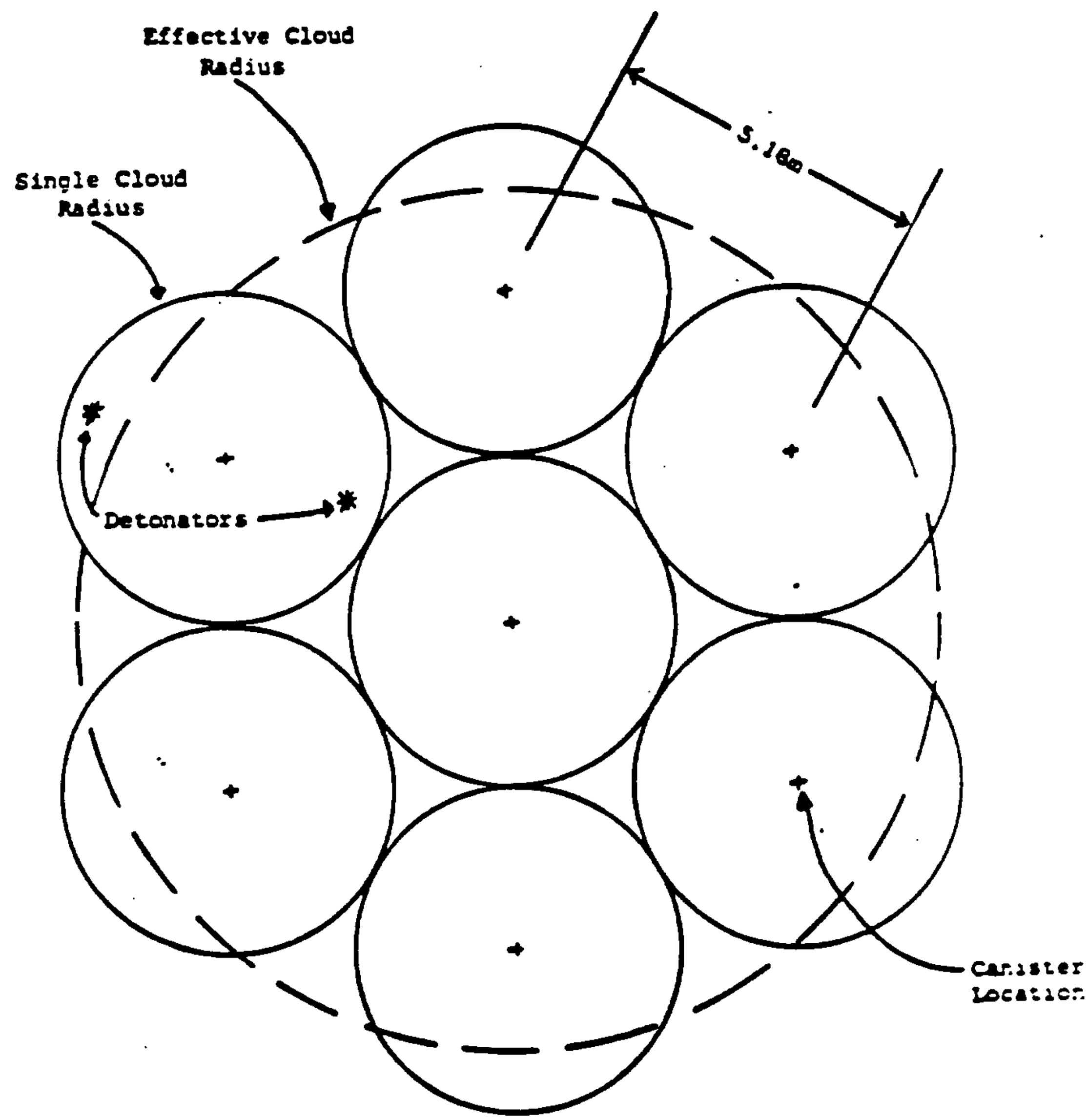


Figure 5.4 Sketch showing the relative positioning of the individual canisters. The seven circles represent the FAE clouds from the

Fuel Mass (g)	Canister Spacing (m)	δt (ms)	t_b (ms)	γ*	Detonation Transfer
14	7.32	60	180	0.667	Yes
14	7.32	100	180	0.440	No
14	7.32	80	200	0.600	Yes
14	7.32	120	180	0.330	Partial
14	7.32	90	180	0.500	No

*γ is the age of second cloud divided by age of first cloud at time of cloud detonation. Single 100 gm Comp C-4 cloud detonator immersed in first cloud.

Table 5.4 Burster Delay, δt (P.O. Fuel) decane, and jet fuel (JP4) have all been shown to detonate in air. The presence of nitrogen in air acts as a detonation inhibitor significantly limiting the range of fuel-air ratios that can be detonated (31) as indicated in Figures 5.1 and 5.2. Within a given range for a given fuel the critical detonation energy can vary by several orders of magnitude. Under ideal circumstances detonation of hydrocarbon fuels requires on the order of 10 to 100 kilojoules which amounts to .002 to 0.02 kilograms of TNT. In practical applications experience has shown that the detonation charge is more typically about 1% of the fuel mass. This suggests that about 4 kilograms of TNT would be required for the EBM warhead, which is not inconsistent with the variability suggested by Figure 5.1. Alternative means of detonation using halogen compounds have been achieved in laboratory experiments but are so undeveloped at this time that a significant developmental program would be required to produce a deployable device.

The delay time between fuel dispersal and detonation is determined largely by the fuel combustion chemistry which requires the FAE cloud to reach the stoichiometric radius. Under typical conditions, this will take between 0.14 to 0.17 seconds as indicated in Figure 5.4. However, scaling laws suggest that detonation of the EBM warhead could be delayed as long as 0.7 to 0.8 seconds if other factors required it.

Multiple fuel clouds could be created by dividing the warhead into several independently dispersed bomblets. Cube root scaling laws suggest an increased kill area advantage by doing this. On the other hand, the advantage may be neutralized by intrinsic structural factors described in Section 7.

6. BLAST

6.1 Background

In many engineering applications, the blast profiles of all explosives are treated identically. This is not surprising given the relatively crude uses to which they have been put. However, in recent decades the growing concern about the effects of nuclear weapons and a realization of the damage potential from natural gas and petrochemical explosions has generated many studies of specific blast phenomena that have revealed important differences between nuclear, fuel-air and conventional high explosive blast profiles. (See Figure 6.1).

The parameters of interest are energy released, time, distance from hypocentre, peak static and dynamic overpressure, and static and dynamic impulse. Numerous theoretical and emperical models exist relating these parameters for each class of explosion listed above. there also exist many models which allow one to compute approximate blast parameters of one class using the better understood processes of another class. For example, blast properties of the conventional high explosive, TNT, have been studied and understood in great detail so there are many models relating nuclear and FAE to TNT. Similarly, as FAE becomes better understood, more models relating FAE to nuclear blast parameters are being developed.

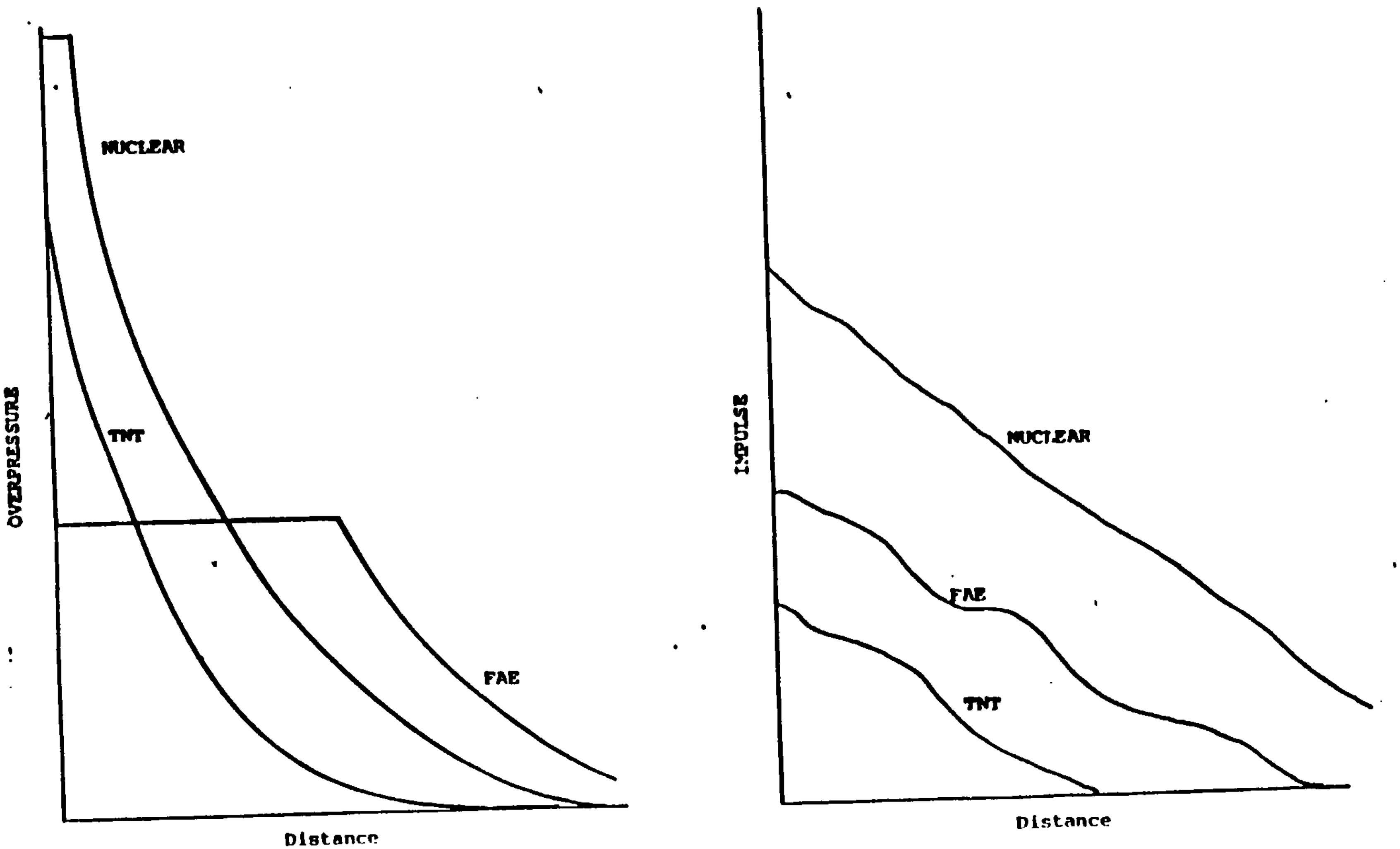


Figure 6.1 Qualitative comparison of blast parameters of conventional, nuclear and FAE explosives of similar yield

Scaling laws have also been developed and expanded which allow one to easily compute blast effects at a given distance for any blast yield when one knows the effects at one distance and yield. The most successful of these is the Hopkinson cube root scaling law.

The most significant differences between conventional high explosives and the others is that TNT and similar explosives produce very high peak overpressures from very nearly a point source, while nuclear and FAE produce peak overpressures over an extended region. Also the overpressure declines with distance much faster with conventional explosives than with nuclear and FAE. Accordingly, models developed for one class of explosive have to be carefully adjusted prior to application to other classes. These adjustments typically are in response to the two blast regions apparent in the FAE overpressure curve in Figure 6.1 which are known as near field and far field. In far field most models are equivalent and effective. It is in the near field, in and near the flat overpressure region inside the cloud, that significant and important differences occur and where the usual scaling laws fail.

6.2 SCALING LAWS

Appropriate scaling laws can be applied in order to calculate the characteristic properties of the blast wave from an explosion of any given energy if those for another energy are known. With the aid of such laws it is possible to express the data for a large range of energies in a simple form.

Theoretically, a given pressure will occur at a distance from the point of detonation that is proportional to the cube root of the energy yield. Full-scale tests have shown this relationship between distance and energy yield to hold for yields over a very large range. Thus, cube root scaling may be applied with confidence over a wide range of explosion energies. According to this law, if D_1 is the distance from a reference explosion of W_1 units of energy at which a certain overpressure or dynamic pressure is attained, then for any explosion of W energy units these same pressures will occur at a distance D given by

$$\left[\frac{D}{D_1}\right] = \left[\frac{W}{W_1}\right]^{1/3}$$

Cube root scaling can also be applied to arrival time of the shock front, positive phase duration, and positive phase impulse, with the understanding that the distances concerned are themselves scaled according to the cube root law. The relationships may be expressed in the form

$$\left[\frac{t}{t_1}\right] = \left[\frac{D}{D_1}\right] = \left[\frac{W}{W_1}\right]^{1/3}$$

and

$$\left[\frac{I}{I_1}\right] = \left[\frac{D}{D_1}\right] = \left[\frac{W}{W_1}\right]^{1/3}$$

where t_1 represents arrival time or positive phase duration,

I_1 is the positive phase impulse for a reference explosion of energy W_1,

t and I refer to any explosion of energy W, and

D_1 and D are distances from ground zero.

6.3 MODELS

6.3.1 Model Selection

Several FAE blast models have been considered, five of which are considered here. The Strehlow (204) and Dow models are essentially TNT blast models not suited to FAE blasts. The Sedov (203) and Kogarko (198) models have been derived specifically for FAE blasts but are for nearly ideal conditions where the fuel air mixture is homogenous and perfectly stoichiometric throughout the aerosol cloud. This is a reasonable assumption for an experimental situation and may even be approached on occasion with conventional FAE bombs such as the CBU-55B. On the other hand, the situation with the EBM is quite different with a larger quantity of fuel propelled at a higher velocity directly down upon a target rather than being spread over it as is the case with bombs. All of these factors will tend to degrade the ideal situation and render the Sedov and Kogarko models less reliable.

Although the Brode model (160) is the oldest of the blast models considered here, it has been modified to fit the FAE condition and especially to illuminate the important new situation with the EBM by introducing the detonation efficiency. The detonation efficiency factor (f) is included (see Equation 6.3-5) which allows one to examine the pressure/radius consequences of fuel air inhomogeneities. In addition, out to the stoichiometric, or detonation radius (r_s) the pressure is truncated at 377 newtons per square centimeter to represent the observed pressure within an exploding FAE cloud.

We have computed and presented in Appendix B the pressure/radius relationship for f values of 1, 5, 50 and 70 percent, using a modified Brode model as described in Section 6.3.3.

6.3.2 Strehlow Model (TNT)

Many existing guidelines for estimating blast damages from chemical explosions are based on the TNT equivalent yield concept. If W_F grams of a certain fuel is released into the atmosphere and H is the standard heat of combustion of this fuel in calories/gram, then the TNT equivalent yield is obtained by

$$W_{TNT} = \frac{\alpha \Delta H \times W_F}{1120} \qquad (6.3\text{-}1)$$

where α is some empirical factor (0<α<<1) and 1120 is the explosion energy of TNT in calories/gram.

Once W_{TNT} is found, a characteristic explosion length R_o defined by

$$R_o = \frac{(W_{TNT} \times 1120)}{P_o}^{1/3} \qquad (6.3\text{-}2)$$

can be calculated. In Equation 6.3-2, W_{TNT} is in grams and P_o is the pressure of the atmosphere in Newton/cm^2 at sea level.

With R_o determined, a standard chart yields the blast overpressure Δps and the impulse I with the scaled distance. This method assumes that the blast from a vapor cloud explosion is equivalent to that from the detonation of a concentrated charge of TNT of mass W_{TNT}.

The empirical factor α in Equation 6.3-1 is used to account for all the differences between both types of explosions. From the reconstruction of past accidents, it is found that α can vary from an insignificant fraction of a percent to values as high as 30%. Even if an adequate value of α were known, the blast wave decay from both types of explosion can only be similar in the far field. In the near field, the blast from a TNT explosion is much stronger and yields much higher blast overpressures than the corresponding values for all fuel air vapor cloud explosions.

It has long been recognized that the TNT equivalent method can yield a very crude estimate. However, due to the large number of unknown factors in most FAE releases it may be argued that they completely overshadow the inadequacies of the TNT equivalent method.

6.3.3 Brode Model (Modified)

The original Brode model (160) was developed for conventional high explosives that more nearly fit the idealized case of a point source explosion. The peak overpressure Δps at high pressure is

$$\Delta ps = 0.1567r^{-3} + 1 \text{ atmos.}$$

The shock radius (r) is in dimensionless units of energy/pressure. At lower pressures the emperical equation below applies

$$\Delta ps = \frac{0.137}{r^3} + \frac{0.119}{r^2} + \frac{0.269}{r} - 0.019 \text{ atmos.}$$

for $0.1 < \Delta ps < 10$ or $0.26 < r < 0.28$

The modified Brode model for nuclear blast simulation may be expressed as follows where P is in psig.

$$P(r,W) = \frac{1.58W}{r^3} + 5.4 \left[\frac{W}{r^3}\right]^{1/2} + 0.0215 \qquad (6.3\text{-}3)$$

r is in thousands of feet and W is in kilotons equivalent yield.

It should be pointed out that W in Equation 6.3-3 is for an equivalent nuclear detonation. But only 50% of the nuclear energy release goes into the blast (with 30% and 40% going into heat and the remainder into nuclear radiation). Consequently, $W/2 = W_o$ where W_o is the total equivalent weight in FAE fuel. However, FAE fuels are k times more energetic than TNT so we get $W/2 = kW_ok$. where k is the energy of explosion (Table 3.4) divided by 1120 giving $W=2kfW_o$. Substituting this into Equation 6.3-3

$$P(r,k,f,w_o) = \frac{3.16kfW_o}{r^3} + 7.6 \left[\frac{kfW_o}{r^3}\right]^{1/2} + 0.0215 \qquad (6.3\text{-}4)$$

This model approximates the FAE case if one truncates the overpressure at 260 psig (377 newtons/cm^2) which is the peak overpressure within the FAE blast cloud for most fuels.

Converting to metric units with P in newtons/cm², r in meters, W_o in kilograms, and k in calories/gram we have

$$P = 0.128 \frac{k\ f\ W_o}{r^3} + 1.84 \left[\frac{k\ f\ W_o}{r^3}\right]^{1/2} + 0.0313 \qquad (6.3\text{-}5)$$

6.3.4 Dow, Sedov, and Kogarko Models (FAE)

The Dow approximation is perhaps the least satisfactory since it does nothing more than modify the TNT model.

$$W_e = 0.23W\ \Delta H_e f \qquad (6.3\text{-}6)$$

where W_e is the TNT equivalent energy in the FAE cloud expressed in grams,

ΔH_e is the net heat of combustion of the released material in btu/lb,

f is an energy yield factor and

W is the weight of the FAE fuel in pounds.

Substituting Equation 6.3-6 into W_{TNT} of Equation 6.3-2 and truncating the pressure at 260 psig, we arrive at the Dow approximation,

$$R_o = \frac{6.34}{P_o} (W\Delta H_e f)^{1/3}$$

which can be solved for overpressure using the same charts as Strehlow.

The Sedov model takes into account the geometry of the cloud through the terms ν and α as well as the source energy E_o and the range r in metres:

$$P = \frac{1.9 \times 10^{-4} E}{(\nu+2)^2(\gamma+1)r^{\nu}}$$

where, $E = E_o/\alpha$,

P is the peak overpressure in Newtons/cm^2, and

γ is the specific heat ratio for air = 1.4.

Table 6.1 gives the geometry dependent values for and α.

FAE Cloud Geometry	ν	α
Plane	1	1.075
Cylindrical	2	1.000
Spherical	3	0.850

TABLE 6.1. Cloud Geometry

The Kogarko model is also empirically derived, and like the others is truncated at 377 N/cm^2 (260 psig) to account for the near field overpressure within the FAE cloud. Peak overpressure, P, in Newtons/cm^2 is

$$P = \frac{0.51}{R^{1.7}} \qquad \text{for } 0.08 \leq R \leq 0.3$$

and

$$P = \frac{0.0061}{R} + \frac{0.0015}{R^2} + \frac{0.00026}{R^3} \qquad \text{for } R > 0.3$$

where $R = rW^{-1/3}$ and

r is range in metres from the blast hypocentre and

W is total combustion energy in kilocalories.

6.4 OVERPRESSURE COMPUTATIONS

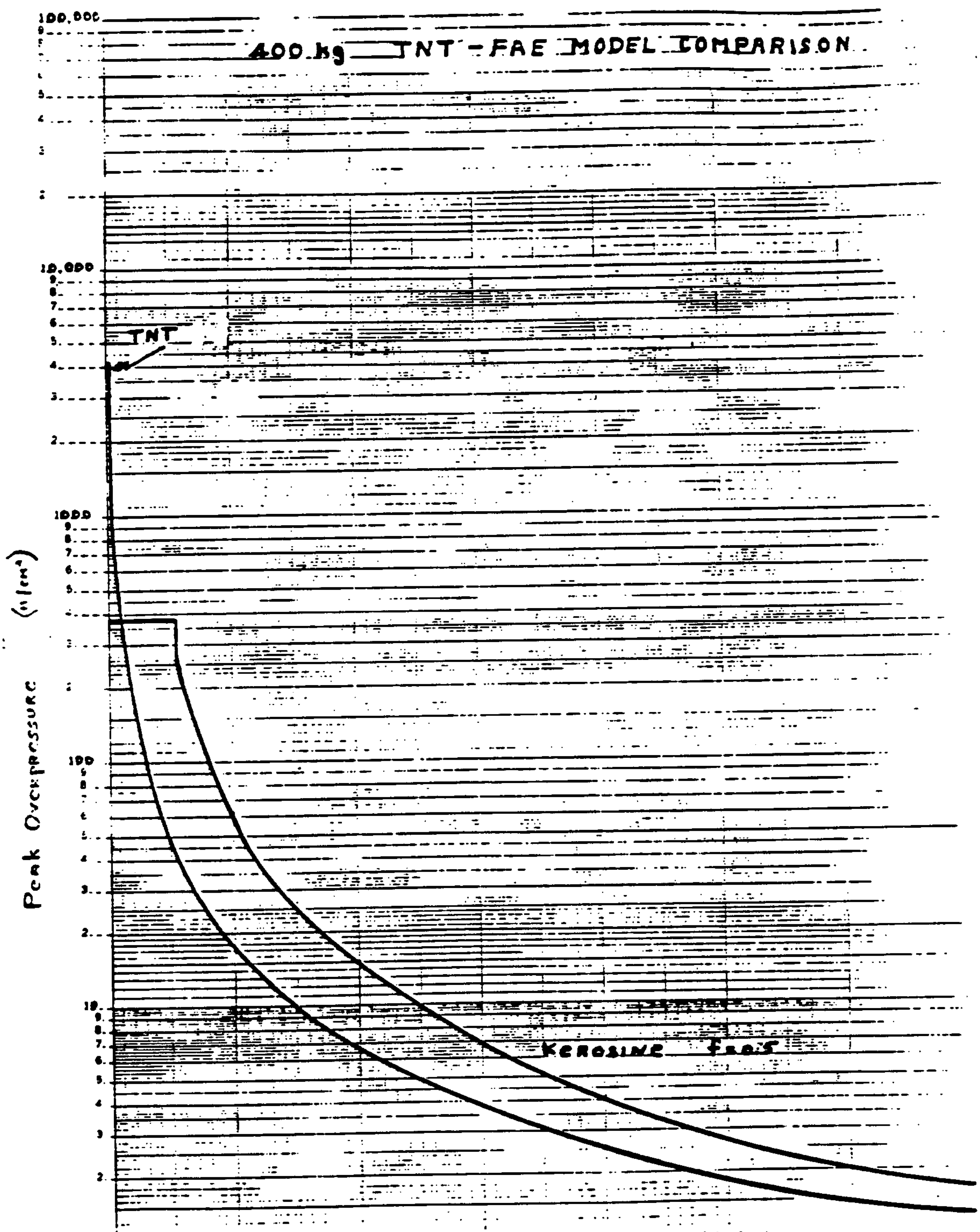
Overpressure curves are shown in Appendix B for the modified Brode model. The cases shown are for a 0.5 cubic metre volume limited payload (V) and a 400 kilogram mass limited payload (M).

It is interesting to note that there is relatively little difference between the mass limited case and the volume limited case, indeed the differences are smaller than the model to model differences.

In Figure 6.2 the modified Brode model is plotted with a TNT curve. The characteristically higher overpressures in the near field for TNT are evident as well as the similarity of models in the far field.

On the basis of a preliminary evaluation of the several models considered here, we conclude that the modified Brode model is the most suitable. The Brode model is quite sensitive to the assumed value of f which is not very well known, and can vary from blast to blast. Accordingly, it may be prudent to use this model with a range of f values.

FIGURE 6.2


400 kg TNT - FAE MODEL COMPARISON
TNT
KEROSINE
Peak Overpressure
100,000
10,000
1000
100
10

6.5 SUMMARY

After examining several blast models, we have selected a modified Brode model for our FAE blast calculations because of the explicit introduction of the detonation efficiency, f. We believe this is prudent because of the challenging problem of fuel dispersal from a reentering KEM warhead with its high speed and vertical trajectory at the burster point over the target. Such a trajectory will lead inevitably to fuel air inhomogeneities within the FAE cloud and consequent deviations from stoichiometry that will reduce the detonation efficiency (f) by some unknown amount. A sense of the range of possible appropriate f values can be obtained from the FAE literature and run at least from 0.0075 (156) to 0.37 (23). By way of comparison, some of the FAE blast models seem to implicitly assume an f value of 0.05 (Kogark [198]) to 0.30 (Sedov [203]). In the ideal case, never attainable in practice, the f value would be 1.0.

In Appendix B we have prepared tables and graphs of peak overpressure vs radius for several values of f. On the basis of this preliminary study, we would suggest assuming a range of f values from 0.05 to 0.5 and carrying out blast calculations and kill probabilities accordingly.

7. WARHEAD CONFIGURATION

7.1 Single vs Multiple FAE Canisters

Detonation of multiple smaller FAE canisters containing a fixed total amount of fuel will cover a greater area with a minimum specified overpressure than can be covered by the detonation of the same amount of fuel in a single large canister. The total area (A_T) of the FAE cloud(s) is:

$$A_T = n\pi r^2 = n\pi r_n^2 \qquad (7.1\text{-}1)$$

where n is the number of FAE cloudlets of radius r_n each.

The kill radius r_n is proportional to the cube root of the explosive yield fraction for each cloudlet (W/n) divided by the peak overpressure at that radius (P_r) where W is the total yield

$$r_n = \frac{k\,(W/n)^{1/3}}{P_r} \qquad (7.1\text{-}2)$$

and k is a constant of proportionality. Combining equations (7.1-1) and (7.1-2) and gathering all the constant terms in g we have

$$A_T = gn^{1/3} \qquad (7.1\text{-}3)$$

It is clear from equation (7.1-3) that for a fixed total yield (W), the total kill area (A_T) increases only slowly with n. For example, one would have to divide the warhead into 8 bomblets to double the total kill area achieved with the same fuel load contained in one large bomb.

However, there is a weight and volume penalty for the creation of multiple bomblets that acts to contain the cube root advantage. The larger n, the larger the penalty, so equation (7.1-3) really looks like

$$A_T = gn^{1/3} C(n) \qquad (7.1\text{-}4)$$

where C(n) is the penalty. An exact analytical expression for C(n) is probably not possible given the practical variables it represents, but it probably looks something like

$$C(n) = f(v)\ h(B)\ q(d)\ m(s)$$

where 1-f(v) is the volume packing fraction loss, 1-h(B) is the loss due to the multiple canister dispersal system, 1-q(d) is the loss due to the structural materials of the multiple canisters, and 1-m(s) is the loss due to unavailable volume in the nose cone. f(v) can be shown to be equal to $n(r/R)^2$ for multiple cylindrical fuel canisters of maximum uniform radius fitting in a warhead of radius R. For the two most practical cases where n=3 and 7 we get f(v) equal to 0.65 and 0.78 respectively. (See Appendix C). h(B) is design dependent but is probably on the order of 0.98.

q(d) can be shown to vary roughly as nr/R which for the 3 and 7 canister cases gives a yield penalty of $(1.5M)^{1/3}$ and $(2.3M)^{1/3}$ respectively, where M is the mass of the cylindrical warhead shell. If the shell is made of 5mm thick aluminum, this leads to a q(d) value on the order of 0.9.

Multiple canisters will also preclude using any of the volume within the conic part of the warhead. Accordingly, the u(s) penalty will be on the order of 0.9.

Combining these factors gives a rough estimate of C(n) = (0.75) (0.98) (0.9) (0.9) = 0.6. Putting this and n=7 bomblets in equation (7.1-4) gives a kill area advantage of 1.1 over the single canister case.

Given the additional complexities of a multiple canister system and the reduced reliability probably accompanying it we would favor the single large warhead.

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Appendix A

Combustion equations for fuels in Table 3.4 with A and B values. Fuel mixtures such as kerosine, etc., have not been included because of the complexity of the combustion equations.

Propylene Oxide: $CH_3(CH\ CH_2)\ O + 4O_2 \longrightarrow 3\ CO_2 + 3\ H_2O$

Heptane: $C_7H_{16} + 11\ O_2 \longrightarrow 7\ CO_2 + 8\ H_2O$

Decane: $C_{10}H_{22} + 15.5\ O_2 \longrightarrow 10\ CO_2 + 11\ H_2O$

Hexane: $C_6H_{14} + 9.5\ O_2 \longrightarrow 6\ CO_2 + 7\ H_2O$

Xylene: $C_8H_{10} + 10.5\ O_2 \longrightarrow 8\ CO_2 + 5\ H_2O$

Petane: $C_5H_{12} + 8\ O_2 \longrightarrow 5\ CO_2 + 6\ H_2O$

Benzene: $C_6H_6 + 7.5\ O_2 \longrightarrow 6\ CO_2 + 3\ H_2O$

Toluene: $C_7H_8 + 9\ O_2 \longrightarrow 7\ CO_2 + 4\ H_2O$

FUEL	A	B
Propylene Oxide	1	4
Heptane	1	11
Decane	1	15.5
Hexane	1	9.5
Xylene	1	10.5
Pentane	1	8
Benzene	1	7.5
Toluene	1	9

Appendix B

Tables and graphs of peak overpressure vs distance for fuels in Table 3.4.

An inspection of the tables shows that there is very little difference between the mass limited case (400 kg) and the volume limited case. Similarly, the fuels tend to be grouped with kerosine, JP4, and diesel fuel in one, pentane, hexane, heptane, and decane in another, and benzene, toluene, and xylene in another. Accordingly, we have plotted the fuels in these groups with just the mass limited case (400 kg). The variation within a group is virtually covered by the thickness of the graph line.

Also included is a comparison of the modified Brode model to the 'Josephson' (China Lake) model for 400 kg of propylene oxide.

FUEL: KERSONE

$k = 10200$ cal/g

$w = 400$ kg <u>mass</u> limited

$w = 400$ kg <u>volume</u> limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128 \frac{k\ fw}{r^3} + 1.84 \left[\frac{kfw}{r^3}\right]^{1/2} + 0.0313$$

f	r_s 11.2 / 11.2	r: 30	50	70	100	150
0.01	13.7/13.7	2.5/2.5	1.12/1.12	0.68/0.68	0.41/0.41	0.24/0.24
0.05	40.8/40.8	6.1/6.1	2.6/2.6	1.5/1.5	0.89/0.89	0.49/0.49
0.50	256/256	25.7/25.7	9.6/9.6	5.3/5.3	2.9/2.9	1.5/1.5
0.70	343/343	32.5/32.5	11.8/11.8	6.4/6.4	3.5/3.5	1.8/1.8

FUEL: JET FUEL

k = 10200 cal/g
w = 400 kg <u>mass</u> limited
w = 390 kg <u>volume</u> limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128 \frac{k f w}{r^3} + 1.84 \left[\frac{kfw}{r^3}\right]^{1/2} + 0.0313$$

	r_s			r		
f	11.2 11.1	30	50	70	100	150
0.01	13.7/13.7	2.5/2.5	1.1/1.1	0.68/0.67	0.41/0.40	0.24/0.23
0.05	40.8/40.8	6.1/6.1	2.6/2.6	1.5/1.4	0.89/0.89	0.49/0.49
0.50	256/256	25.7/25.7	9.6/9.6	5.3/5.2	2.9/2.9	1.5/1.5
0.70	343/344	32.5/31.9	11.8/11.6	6.4/6.3	3.5/3.5	1.8/1.8

FUEL: DIESEL FUEL

$k = 10200$ cal/g

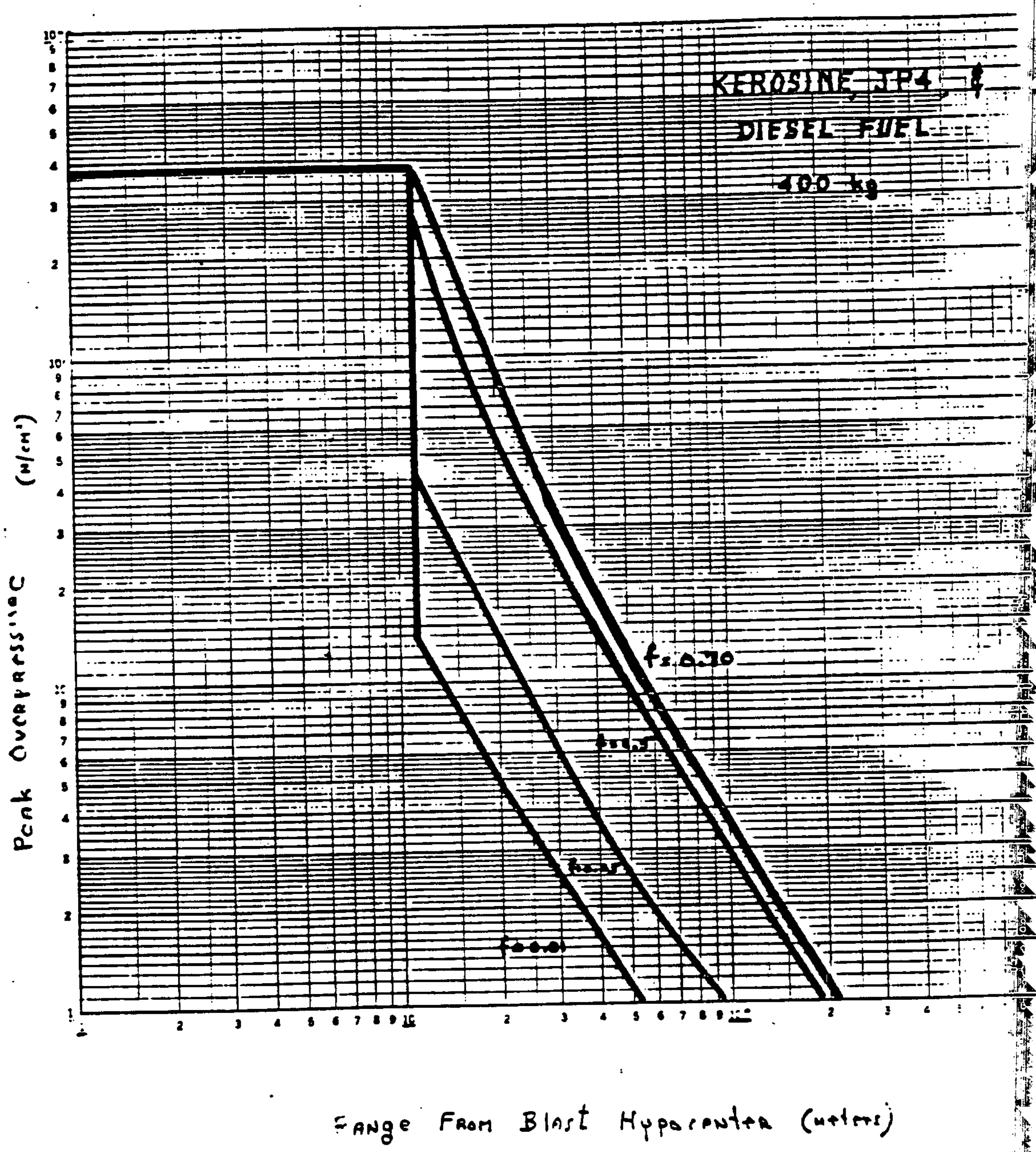
$w = 400$ kg <u>mass</u> limited

$w = 420$ kg <u>volume</u> limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128 \frac{k\,fw}{r^3} + 1.84 \left[\frac{kfw}{r^3}\right]^{1/2} + 0.0313$$

f	r_s 11.1 / 11.3	r: 30	50	70	100	150
0.01	13.9 / 13.9	2.5 / 2.6	1.1 / 1.2	0.68 / 0.70	0.41 / 0.42	0.24 / 0.24
0.05	41.6 / 41.4	6.1 / 6.2	2.6 / 2.7	1.5 / 1.6	0.89 / 0.91	0.49 / 0.50
0.50	262 / 261	25.7 / 26.6	9.6 / 9.8	5.3 / 5.4	2.9 / 3.0	1.5 / 1.6
0.70	351 / 350	32.5 / 33.6	11.8 / 12.1	6.4 / 6.6	3.5 / 3.6	1.8 / 1.9



KEROSINE, JP4, &
DIESEL FUEL
400 kg
f=0.30
f=0.1
f=0.05
f=0.01
Peak Overpressure (N/cm²)
Range From Blast Hypocenter (meters)

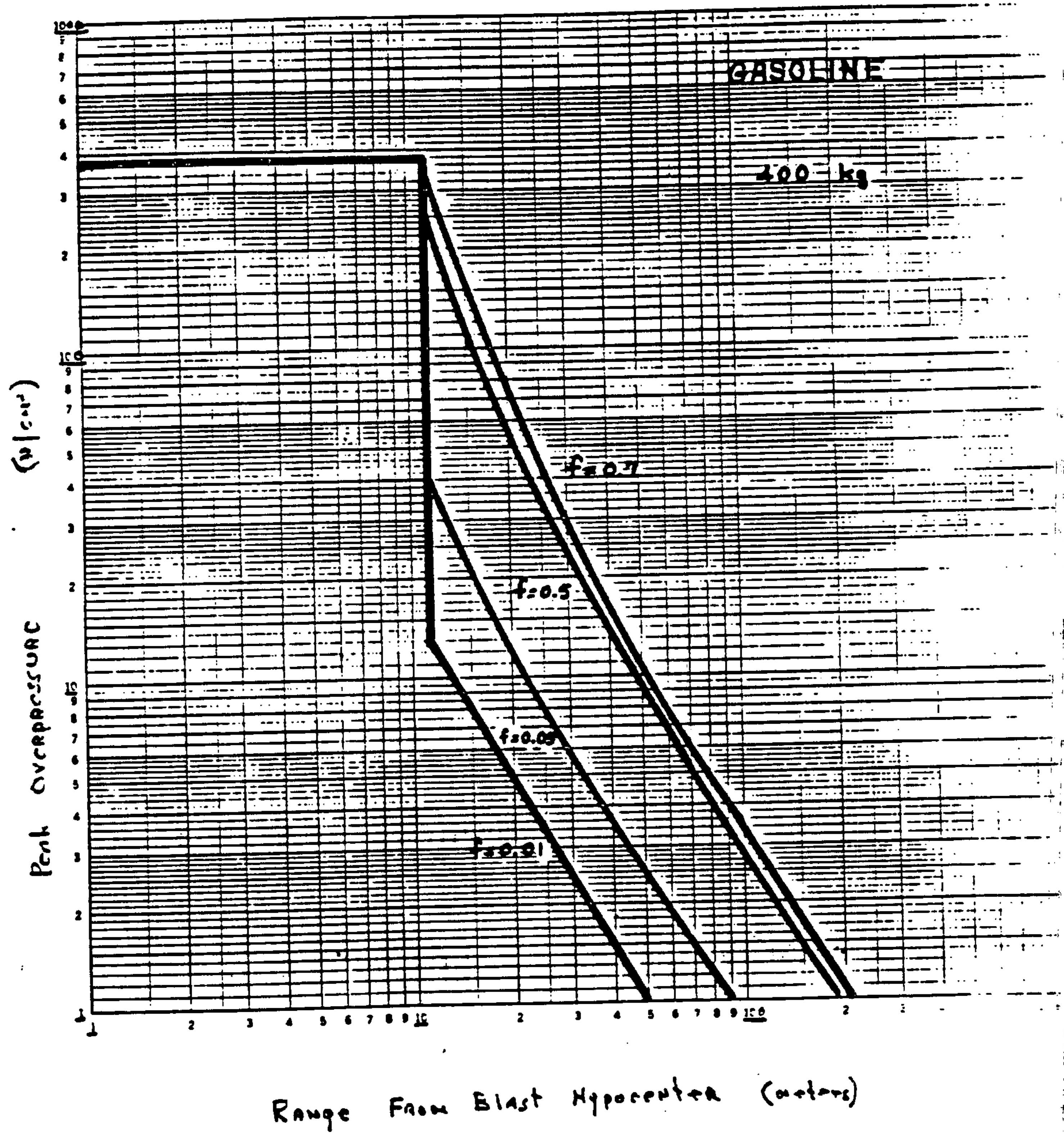
FUEL: GASOLINE

k = 10200 cal/g
w = 400 kg <u>mass</u> limited
w = 340 kg <u>volume</u> limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128\,\frac{k\,f\,w}{r^3} + 1.84\left[\frac{kfw}{r^3}\right]^{1/2} + 0.0313$$

f	r_s 11.5 / 10.9	r = 30	50	70	100	150
0.01	13.0 / 13.0	2.5 / 2.3	1.1 / 1.0	0.68 / 0.63	0.41 / 0.38	0.24 / 0.22
0.05	38.5 / 48.5	6.1 / 5.5	2.6 / 2.4	1.5 / 1.4	0.89 / 0.82	0.49 / 0.45
0.50	239 / 239	25.7 / 23.0	9.6 / 8.7	5.3 / 4.8	2.9 / 2.7	1.5 / 1.4
0.70	320 / 320	32.5 / 29.0	11.8 / 10.6	6.4 / 5.8	3.5 / 3.2	1.8 / 1.7


GASOLINE
400 kg
f=0.7
f=0.5
f=0.05
f=0.01
Peak Overpressure (N/cm²)
Range From Blast Hypocenter (meters)

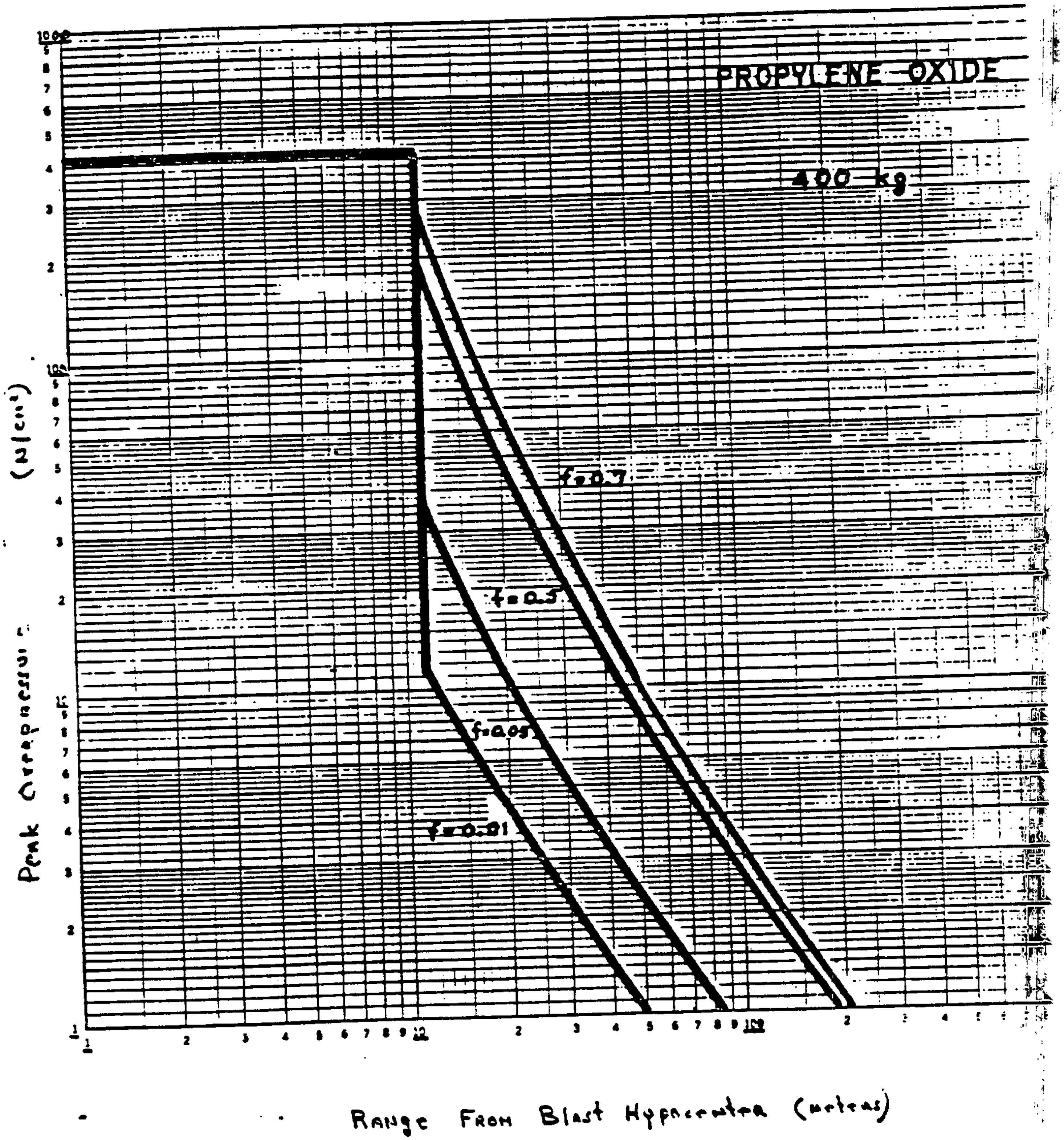
FUEL: PROPYLENE OXIDE

k = 7900 cal/g
w = 400 kg mass limited
w = 415 kg volume limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128 \frac{k\,fw}{r^3} + 1.84 \left[\frac{kfw}{r^3}\right]^{1/2} + 0.0313$$

f	r_s 11.5 / 11.6	r = 30	50	70	100	150
0.01	11.1/11.2	2.2/2.2	1.0/1.0	0.60/0.61	0.36/0.37	0.21/0.21
0.05	32.1/32.3	5.2/5.3	2.3/2.3	1.3/1.4	0.78/0.80	0.44/0.44
0.50	192/194	21.6/22.1	8.2/8.4	4.6/4.7	2.5/2.6	1.4/1.4
0.70	256/259	27.2/27.9	10.0/10.3	5.5/5.6	3.1/3.1	1.6/1.6



PROPYLENE OXIDE
400 kg
f=0.7
f=0.5
f=0.05
f=0.01
Peak Overpressure (N/cm²)
Range From Blast Hypocenter (meters)

FUEL: PENTANE

$k = 11{,}100$ cal/g
$w = 400$ kg <u>mass</u> limited
$w = 315$ kg <u>volume</u> limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128 \frac{k\,fw}{r^3} + 1.84 \left[\frac{kfw}{r^3}\right]^{1/2} + 0.0313$$

f	r_s 13.5 / 12.4	r: 30	50	70	100	150
0.01	10.2 / 10.3	2.6 / 2.3	1.2 / 1.0	0.71 / 0.63	0.42 / 0.38	0.24 / 0.22
0.05	29.1 / 29.4	6.4 / 5.5	2.7 / 2.4	1.6 / 1.4	0.93 / 0.82	0.51 / 0.46
0.50	171 / 173	27.2 / 23.1	10.1 / 8.7	5.5 / 4.8	3.1 / 2.7	1.6 / 1.4
0.70	227 / 230	34.5 / 29.2	12.4 / 10.7	6.7 / 5.9	3.7 / 3.2	1.9 / 1.7

FUEL: HEXANE

k = 11,100 cal/g
w = 400 kg <u>mass</u> limited
w = 330 kg <u>volume</u> limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128 \frac{k\,fw}{r^3} + 1.84 \left[\frac{kfw}{r^3}\right]^{1/2} + 0.0313$$

f	r_s 13.4 / 12.6	r 30	50	70	100	150
0.01	10.3 / 10.2	2.6 / 2.3	1.2 / 1.1	0.71 / 0.65	0.42 / 0.39	0.24 / 0.22
0.05	29.5 / 29.4	6.4 / 5.7	2.7 / 2.4	1.6 / 1.4	0.93 / 0.84	0.51 / 0.47
0.50	174 / 173	27.2 / 23.9	10.1 / 8.9	5.5 / 5.0	3.1 / 2.8	1.6 / 1.5
0.70	232 / 230	34.5 / 30.1	12.4 / 11.0	6.7 / 6.0	3.7 / 3.3	1.9 / 1.7

FUEL: HEPTANE

$k = 11{,}200$ cal/g
$w = 400$ kg mass limited
$w = 340$ kg volume limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128 \frac{k\,fw}{r^3} + 1.84 \left[\frac{kfw}{r^3}\right]^{1/2} + 0.0313$$

	r					
f	r_s 13.0 / 12.3	30	50	70	100	150
0.01	11.0 / 11.0	2.6 / 2.4	1.2 / 1.1	0.71 / 0.66	0.43 / 0.40	0.24 / 0.23
0.05	31.7 / 31.7	6.4 / 5.8	2.7 / 2.5	1.6 / 1.5	0.97 / 0.85	0.51 / 0.48
0.50	189 / 190	27.4 / 24.5	10.1 / 9.2	5.6 / 5.1	3.1 / 2.8	1.6 / 1.5
0.70	252 / 253	34.7 / 31.0	12.5 / 11.3	6.8 / 6.2	3.7 / 3.4	1.9 / 1.8

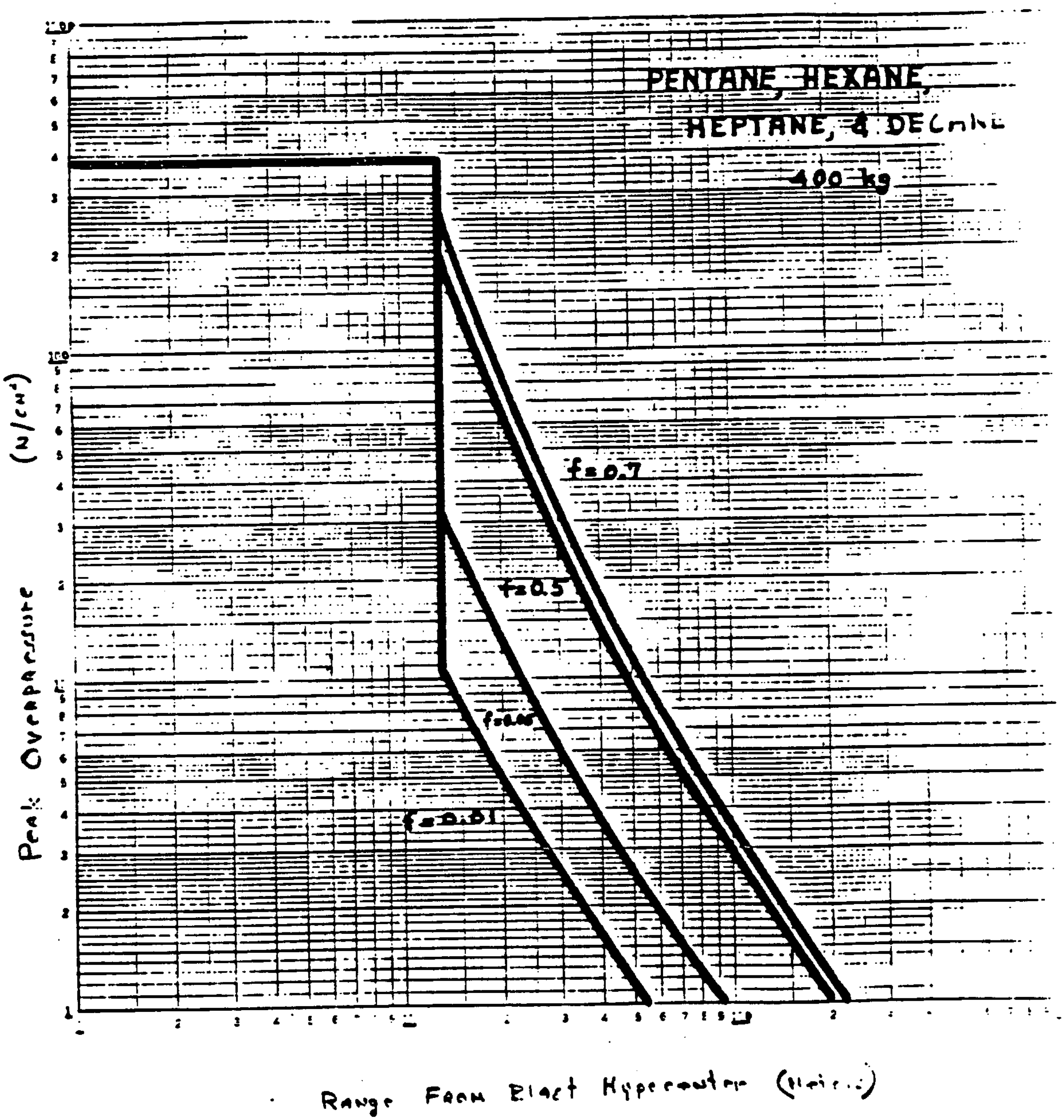
FUEL: DECANE

k = 11,300 cal/g
w = 400 kg <u>mass</u> limited
w = 375 kg <u>volume</u> limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128 \frac{k\,fw}{r^3} + 1.84 \left[\frac{kfw}{r^3}\right]^{1/2} + 0.0313$$

f	r_s 13.4 / 13.1	r: 30	50	70	100	150
0.01	10.4/10.4	2.6/2.5	1.2/1.1	0.72/0.69	0.43/0.42	0.25/0.24
0.05	30.0/30.0	6.4/6.2	2.7/2.6	1.6/1.6	0.93/0.91	0.52/0.50
0.50	177/177	27.6/26.4	10.2/9.8	5.6/5.4	3.1/3.0	1.6/1.6
0.70	235/236	35/33	12.5/12.0	6.8/6.5	3.7/3.6	1.9/1.9



PENTANE, HEXANE,
HEPTANE, & DECANE
400 kg
f=0.7
f=0.5
f=0.01
Peak Overpressure (N/cm²)
Range From Blast Hypocenter

FUEL: BENZENE

k = 9400 cal/g
w = 400 kg <u>mass</u> limited
w = 440 kg <u>volume</u> limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128 \frac{k\,fw}{r^3} + 1.84 \left[\frac{kfw}{r^3}\right]^{1/2} + 0.0313$$

				r		
f	r_s 12.8 / 13.2	30	50	70	100	150
0.01	10.1 / 10.1	2.4 / 2.5	1.1 / 1.1	0.65 / 0.69	0.39 / 0.41	0.23 / 0.24
0.05	28.9 / 29.0	5.8 / 6.1	2.5 / 2.6	1.5 / 1.5	0.85 / 0.89	0.47 / 0.49
0.50	170 / 170	24.3 / 25.9	9.1 / 9.6	5.0 / 5.3	2.8 / 2.9	1.5 / 1.6
0.70	226 / 226	30.7 / 32.8	11.2 / 11.9	6.1 / 6.5	3.4 / 3.5	1.8 / 1.8

FUEL: TOLUENE

k = 9700 cal/g
w = 400 kg <u>mass</u> limited
w = 435 kg <u>volume</u> limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128\,\frac{k f w}{r^3} + 1.64\left[\frac{k f w}{r^3}\right]^{1/2} + 0.0313$$

f	r_s 12.9 / 13.3	r = 30	50	70	100	150
0.01	10.2 / 10.1	2.4 / 2.5	1.1 / 1.1	0.66 / 0.69	0.40 / 0.41	0.23 / 0.24
0.05	29.1 / 28.9	5.9 / 6.2	2.5 / 2.6	1.5 / 1.6	0.87 / 0.90	0.48 / 0.50
0.50	171 / 170	24.8 / 26.3	9.3 / 9.8	5.1 / 5.4	2.8 / 3.0	1.5 / 1.6
0.70	227 / 226	31.4 / 33.3	11.4 / 12.0	6.2 / 6.5	3.4 / 3.6	1.8 / 1.9

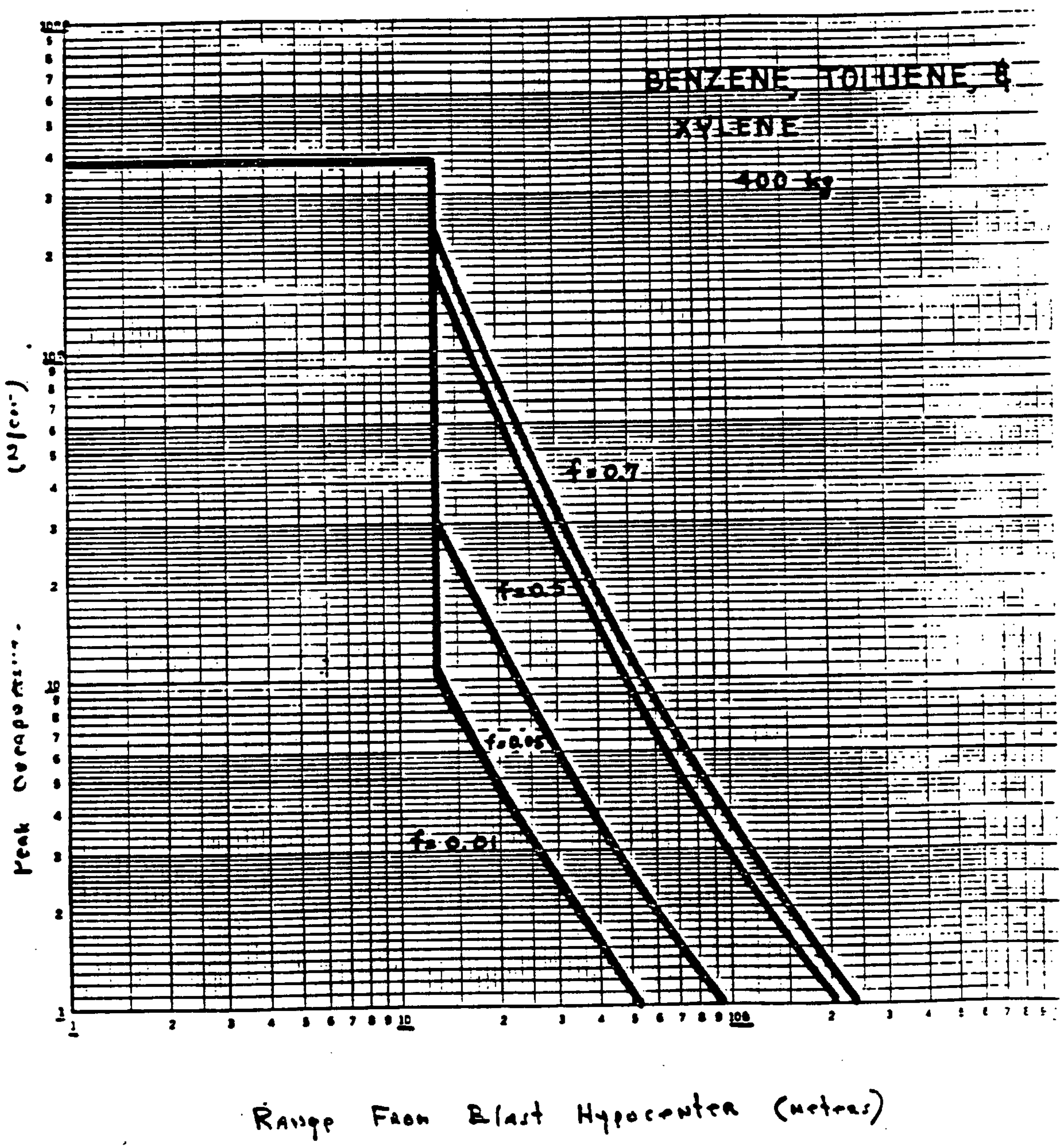
FUEL: XYLENE

$k = 10{,}000$ cal/g
$w = 400$ kg **mass** limited
$w = 430$ kg **volume** limited

Table lists computed peak overpressures (P_m/P_v) for mass limited (P_m) and volume limited (P_v) cases. P_s are in newtons/cm^2, r is distance from blast hypocenter in meters, and f is detonation efficiency.

$$P = 0.128 \frac{kfw}{r^3} + 1.84 \left[\frac{kfw}{r^3}\right]^{1/2} + 0.0313$$

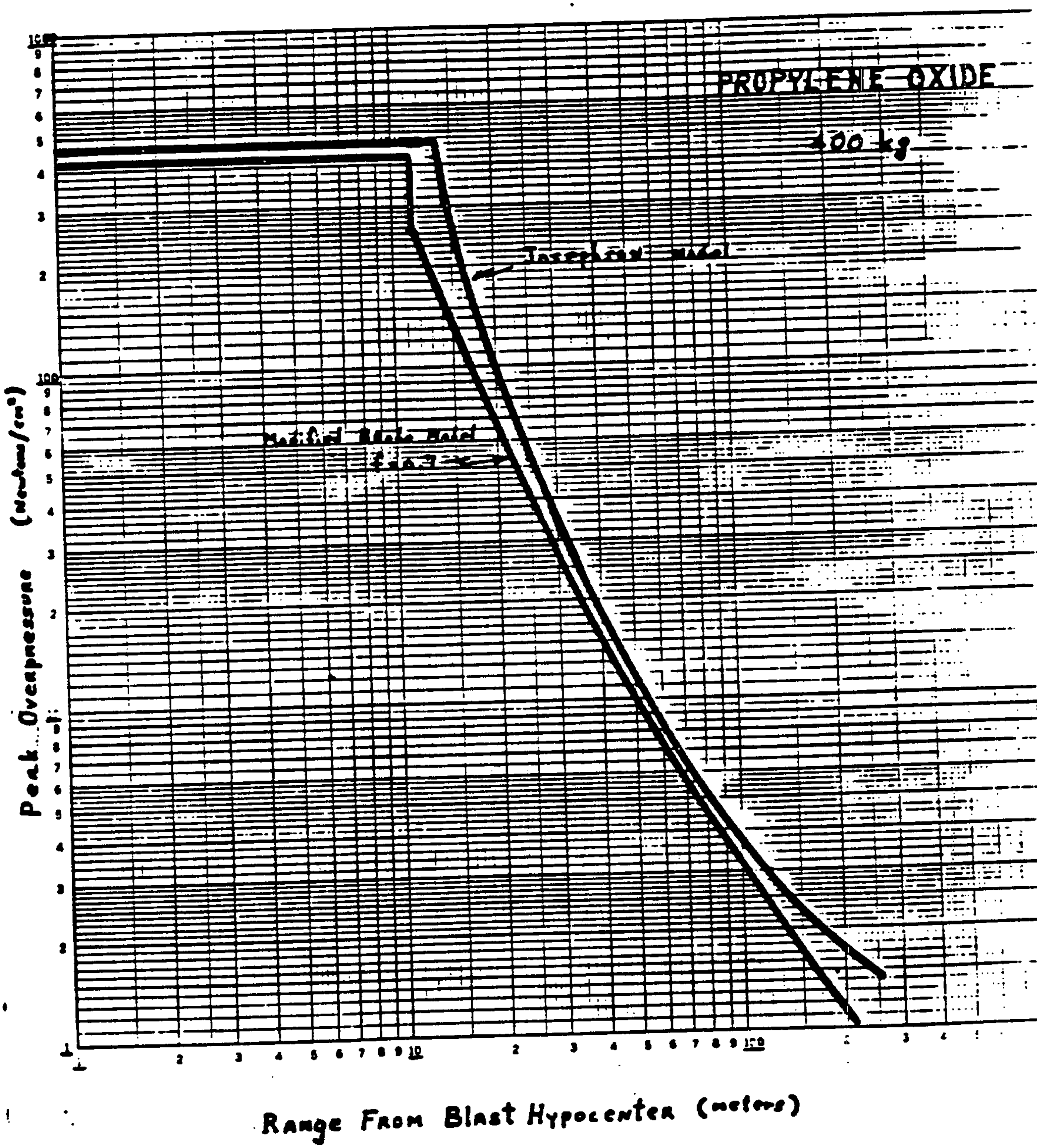
f	r_s 13.0 / 13.3	r = 30	50	70	100	150
0.01	10.2 / 10.2	2.5 / 2.6	1.1 / 1.2	0.67 / 0.70	0.40 / 0.42	0.23 / 0.24
0.05	29.2 / 29.3	6.0 / 6.2	2.6 / 2.7	1.5 / 1.6	0.88 / 0.91	0.49 / 0.50
0.50	172 / 173	25.4 / 26.6	9.4 / 9.9	5.2 / 5.4	2.9 / 3.0	1.5 / 1.6
0.70	229 / 230	32.0 / 33.7	11.6 / 12.1	6.3 / 6.6	3.5 / 3.6	1.8 / 1.9



BENZENE, TOLUENE, &
XYLENE
400 kg
f=0.7
f=0.5
f=0.05
f=0.01
Peak Concentration (N/cm²)
Range From Blast Hypocenter (meters)

MODEL COMPARISON

PEAK OVERPRESSURE VS DISTANCE



Appendix C

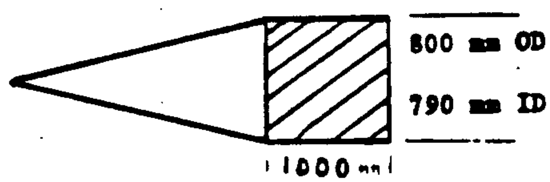
EBM warhead outline and submunition packing.

The assumed warhead size, shape, and weight are in accordance with information presented by Keith Smith (205).

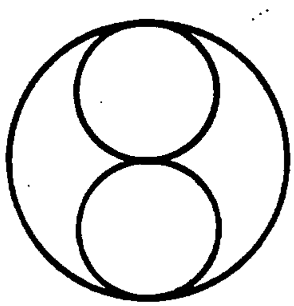
Mass limit is 400 kg.

Volume limit is 0.5 m^3.

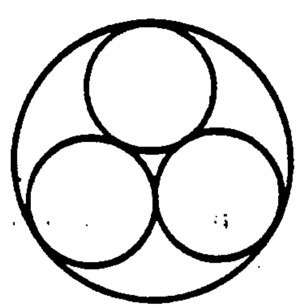
Shape is a right circular cylinder



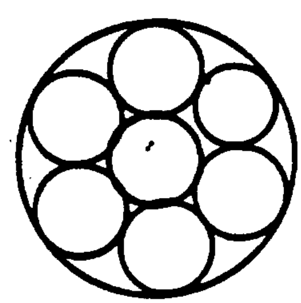
Examples of submunition (FAE bomblets) packing assuming all bomblets in an individual case are the same maximum diameter that will fit within the EBM ID. Cases for numbers of bomblets (n) for n = 2, 3, and 7 are shown with the packing efficiency f(v). Under the restrictions above, n = 7, 'close packed hexagonal' is the most efficient in principle.



n = 2, f(v) = 0.5



n = 3, f(v) = 0.646



n = 7, f(v) = 0.78