THE EFFECTS OF THE IGNITION OF A MAJOR FUEL SPILLAGE

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This paper describes the various forms of damage which may result from the ignition of a major fuel spillage. The paper also tries to expand the understanding of Boiling Liquid Expanding Vapour Explosions, flash and pool fires and the events which happen during and after the ignition using facts from incidents and also a literature survey of experimental work.

INTRODUCTION

In the handling of hydrocarbons the worst conceivable event is likely to be the result of an uncontrolled massive and rapid release of hydrocarbon into the atmosphere.

What happens following the release depends upon its rate of release, the manner in which it is released, the point of release, the properties of the hydrocarbon and if/when it is ignited.

The final outcome will be a blend of one or more of the following situations which for ease of discussion have been divided into distinct categories.

1.0 EVENTS FOLLOWING THE ESCAPE OF COMBUSTIBLE FLUIDS

1.1 No Ignition

The vapour will in time disperse without any blast or fire effects. However, many gases produce toxic effects at concentrations well below their lower flammable limits and in high concentrations the gases may behave as an asphyxiant.

In the context of this paper this topic need not be elaborated upon other than to say that dispersion without ignition does not necessarily equate to safe dispersion.

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1.2 Delayed Ignition

1.2.1 Unconfined Vapour Cloud Explosion (UVCE)

a) Results. Peak over-pressures of about 0.7 to 1 bar will be experienced at the cloud boundary.

Major structural damage will be experienced up to about 100 metres from the release point and in the case of large releases beyond this. Glass damage will be experienced up to 500 metres from the release point and possibly up to several kilometres.

Localised scorching and soot deposition may be experienced.

b) Conditions Favouring a UVCE. The rapid release of a flammable fluid coupled with moderate dispersion such as to produce a very large flammable air and hydrocarbon cloud, usually with some degree of confinement.

1.2.2 Confined Explosion

a) Results. Peak over-pressures of up to 8 bar can be experienced in a fully confined explosion (and very much higher in the unlikely event of a detonation occurring).

b) Conditions Favouring a Confined Explosion. The release of a flammible fluid into a zone where its spread may be restricted or the expansion of the burning cloud may be impeded.

The mass may be relatively small (less than 5 Kgs) if it is confined in, say, a reactor bay.

1.2.3 Flash Fire

a) Results. Over-pressures will be from barely detectable, to sufficient to break glass. The damage will in general include scorching and soot deposition and could extend over many thousands of square metres.

b) Conditions Favouring a Flash Fire. The steady release of a flammable fluid coupled with poor dispersion of the flammable fluid.

1.3 Ignition Already Present

1.3.1 Pool, Running or Torch Fires

a) Results. All of these fires could lead to a BLEVE. The damage will vary according to the nature of the fire. Torch and pool fires will produce localised intense fire damage. Running fires will produce less intense, but more widespread fire damage.

In all cases the intensity of thermal radiation received at any one point will be a complicated relationship between the size and shape of the flame surface, the distance between the flame and the point in question and also the nature of the flame itself.

b) Conditions Favouring Pool, Running or Torch Fires. The steady release of a flammable fluid into an already established fire. The spread of fuel must be restricted by the release rate, natural or plant barriers to create a pool fire. The total spread need not be restricted to create a running fire. To create a torch fire the fuel must be restricted as a strongly directional jet.

1.3.2 Boiling Liquid Expanding Vapour Explosion (BLEVE)

a) Results. A large fireball rising slowly in the air and lasting many seconds. Blast over-pressures at the source will be of the order of 0.05 bar.

b) Conditions Favouring a BLEVE. The sudden release of the flammable contents of a pressurised tank or tanker into an already established fire.

2.0 BLEVES

2.1 Appearance

The growth of a fireball was examined by reference to a film of a large BLEVE (80 te of LPG) (1) which was viewed on a frame by frame basis. The history can be divided into three phases. (Fireballs of different sizes will follow the same basic pattern, but the time intervals will be different from those below).

Phase 1 - Growth

This phase occupied two intervals of about one second each. In the first interval the flame boundary was bright with yellowish-white flames indicating temperatures of about 1300° C. During this interval the fireball reached about half its final diameter. Calculations show that droplets of less than 4 to 5mm diameter will be fully vaporised inside one second and so this phase probably represented the vaporisation and partial superheat of the cloud. During this first interval there would have been reasonably good fuel/air mixing through two mechanisms:-

a) the turbulent wake induced behind the high velocity flashed fluid droplets as described by McQuaid (2).

and

b) the bulk mixing between the fuel vapour and the air.

In the second interval the fireball grew to its final diameter, but became more sooty with colours varying between yellowish-white through to light red indicating flame temperatures in the range of 1300° C to 900 °C. About 10% of the surface was dark and sooty and the other 90% roughly equally divided between yellowish-white, yellowish-orange and light red. This gave an effective radiating temperature of between 1100° C and 1200 °C. During this second interval the fuel/air mixing would have been dominated by the bulk mixing process as the high velocity flash fluid droplets would have expended their momentum and evaporated in the first interval.

Phase 2 - Steady Burning

This phase lasted about 10 seconds during which the fireball did not grow. The flame was noticeably smokey with flame colours varying between yellowish-white and light red. This indicated flame temperatures between 1100° C and 1200 °C.

The fireball was roughly spherical with localnodular billows on the surface. The fireball started to rise at the beginning of this period and changed to the traditional mushroom shaped toroidal cloud on a "stalk". The cloud came under the influence of the wind and started to drift. Air was entrained into the cloud through local turbulence at the surface and also at the centre of the toroid through the thermal recirculation of the cloud itself. The fuel air mixing appeared to be more effective than a pool fire, but less effective than a well aerated turbulent flame.

Phase 3 - Burn Out

This phase lasted about 5 seconds during which the fireball did not appear to change in size. The flame became less sooty and appeared to become translucent.

During this period it is thought that small localised pockets of unburnt gas scattered throughout the original envelope of the fireball finally burnt out. The pockets have both a large surface to volume ratio and are in an environment which has become turbulent due to the rising thermals. Both conditions would encourage a less smokey combustion.

2.2 Size of the BLEVE

The following are four of the several methods proposed for calculating the size of fireballs.

a) Hazagowa for n-pentane (3)

$D = 5.28W^{0.277}$

D = diameter in metres; W = weight of fuel in kg

b) Fay for Hydrocarbons (4)

$D = 2.91W^{0.325}$

D = diameter in metres; W = weight of fuel in kg

c) Brasie (5)

$D = 9.82\ W^{0.320}$

D = diameter in feet; W = weight of fuel in lb

d) Hardee (for LNG) (6)

$D = 3.12\ W^{1/3}$

D = diameter in metres; W = weight of fuel in kg

The diameter of the fireball is defined as the diameter of the sphere which would include the mushroom shaped fireball. This therefore includes some element of averaging.

The three methods proposed for sizing fireballs (b), (c) and (d) suggest that the diameter is approximately proportional to the third root of the mass of fuel.

The first two methods for calculating the size of the fireball are based on relatively small charges of specific fluids.

Although methods (b) and (c) give remarkably similar results, Brasie's equation is derived from the work of High (Ref. 7) on the aborting of the launches of liquid fuelled rockets where the weight of fuel "W" includes the oxidant. Further the abort of the rockets involves a more intimate mixing of the fuel and oxidant (liquid oxygen) and a higher flame temperature than would be experienced with BLEVES. This could lead to some errors if applied to BLEVES.

An alternative method is proposed for the sizing of BLEVES.

The volume of a sphere of hydrocarbon of weight W tonnes, molecular weight M at 1300° C is given by the equation:

$$D = 61\ x\left(\frac{W}{M}\right)^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where D is in metres and W in tonnes

(or in fps units

$$D = 15.5\ x\left(\frac{W}{M}\right)^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where D is in feet and W is in lbs)

The actual flame boundary will however, extend considerably beyond the unburnt fuel core. It is now necessary to study the reports of large BLEVES in order that the constants of the following equation can be established.

$$D = k_1\left(\frac{W}{M}\right)^{1/3}, \ldots\ldots\ldots\ldots \quad (3)$$

D = diameter in metres, W = weight of fuel in te,
M = molecular weight

$$D = k_2\left(\frac{W}{M}\right)^{1/3}, \ldots\ldots\ldots\ldots \quad (4)$$

D = diameter in feet, W = weight of fuel in lbs, M = molecular weight

There are 3 incidents which might prove useful:-

1. Oneonta (8) Charge 80 te of LPG, diameter 400 ft.
2. Kingman (1) Diameter 400 ft., duration 10-15 seconds. The tank size was estimated to be about 150 te and it will be taken that it was half full.
3. Houston (1, 9) Diameter 300 to 350 ft. Charge 50 te of VCM.

Ref. 10 shows clearly the shape of the fireball resulting from a BLEVE at Crescent City involving a Jumbo LPG tanker.

A fifth incident at Belt (11) is quoted as producing a fireball 1,000 feet in diameter. This is inconsistent with the ground scorch patterns which did not extend more than 500 feet diametrically and the survival of firemen 200 feet from the fire seat. It is concluded that there has been an overestimate in the panic of the moment.

Taking the first three incidents, the following table can be drawn up:

Incident	D	D ft.	Mass tonne	M	k_1	k_2
Oneonta	122	400	80	44	99.8	25.2
(Kingman	122	400	75	44	102.1	25.7)
Houston	99	325	50	62.5	106.6	26.9

$$\text{Diameter} = 105\left(\frac{W}{M}\right)^{1/3}, \ldots\ldots\ldots\ldots \quad (5)$$

D = diameter in metres, W = weight of fuel in tonnes
M = molecular weight

or

$$\text{Diameter} = 26\left(\frac{W}{M}\right)^{1/3}, \ldots\ldots\ldots\ldots \quad (6)$$

D = diameter in feet, W = weight of fuel in lbs
M = molecular weight

It is worth comparing the results of calculations using the 5 methods proposed against observed results.

	DIAMETER (m)					
Wt. of Fuel	Hazagowa	Fay	Brasie	Hardee	This Paper	Observed
80 te LPG (8)	120.4	114.1	142.8	134.4	130.2	122
50 te VCM (1, 9)	105.7	98.0	122.8	114.9	97.5	99
6.23 kg Hydrogen (12)	8.76	5.27	6.92	5.7	15.3	14.6-18
1 te n-Pentane	35.8	32.4	35.1	31.2	25.2	-
1 te LPG	35.8	32.4	35.1	31.2	30.2	-
1 te LNG	35.8	32.4	35.1	31.2	41.7	-

The equations 5 and 6 proposed in this paper, have a wider range of application and are preferred to that of Hazagowa, Fay or Brasie for universal use, particularly for BLEVES where the weight of fuel is greater than 1 te. The various correlations are shown in Figure 1.

2.3 Safe Approach for Humans to Vessels on Fire

2.3.1 Blast. It is difficult to separate the blast effects resulting from the initial ignition of the leak ('chemical' blast) and the blast effect as the container erupts ('physical' blast).

The NFPA film on BLEVES (1) shows people being bowled over by the physical blast at Houston and the NTSB report (11) reports firemen being bowled over at Belt. The NTSB report (8) reports damage up to 3/4 mile from the fire seat and 'explosions' during the actual rupture of the tankers. This is not borne out by observation of the NFPA film (1) where there was evidence of the tanker shell peeling back over a period of about 1/5 second. This is fairly typical of the hot ductile failure of steel.

These incidents suggest that close in to the container the 'physical' blast during the rupture is equivalent to a wind of about 100 km/hr. This will inevitably be less than any 'chemical' blast caused by the ignition of the initial leak.

2.3.2 Projectiles. With the exception of Eagle Pass (14) where a tanker disintegrated, all of the BLEVES studied produced few, but large projectiles.

There is no record of projectiles travelling over 600 metres and the vast majority travelled less, as seen at Belt, Oneonta and Des Moines (11, 8, 9).

At Belt, Oneonta, Des Moines, New Jersey Turnpike and Crescent City, (11, 8, 9) and Kingman (1), the tanker ends tore off the body and travelled in a direction roughly axially to the tanker body. This is not a general rule as one end of a tanker at Crescent City (9) appears to have travelled at right angles to the shell. All of these reports plus one at Laurel (9), suggest that tanker barrels (excluding bogies and wheels) do not produce more than 5 fragments in a BLEVE.

There are many reports of secondary fires around crash sites. Unfortunately, the reports are in general imprecise and do not indicate whether the fire resulted from thermal radiation from fuel spilling from rocketting sections of tankers.

There is however, one incident at Laurel (9) where burning rubber ingots were blown up to one mile by the initial 'chemical' blast.

2.3.3 Survival of Humans. In BLEVES there is positive evidence of survivors some 30-60m from the release point. The NFPA film (1) shows firemen about 30m from the tanker at Houston. A photograph taken at Oneonta shows a fireman a like distance away from a tanker. The location of 8 injured persons (non serious) is shown at the New Jersey Turnpike (9). This incident involved less than 20 tons of hydrocarbon. The nearest person at this incident was no more than 30m from the release point. In the same incident there is a report that 'a flaming mass came directly over' a water tender 100 metres south of the release point and one of the tanker ends landed 160m south-east of the release point. Was the flaming mass the tanker end or the fireball?

At Belt, (11) 'at least 10 firemen were within 30 metres of the tanker car' when it erupted - only one was injured.

In this particular incident, the scorch pattern on the ground was very clearly to one side of the tanker. All of this evidence seems to be inconsistent with the fireball diameters quoted earlier - but is it?

Firemen will approach from upwind of the fire. The wind will blow the flames round the leeside of the tanker which will then become hotter than the windward side. The tanker will rupture at its weakest point, this will probably be its hottest point which will be in the unwetted section of the vessel on the leeward side. This means that the contents of the tanker will be displaced some distance leeward from the fire-seat as indicated in (1 and 11).

This subjective analysis is consistent with the survival of firemen close to the fire-seat.

Hazagowa (2) quotes measured flame temperatures in fireballs of 1180 to 1225° C. These values are very close to the temperatures quoted in section 4.1 derived by colormetric assessment. As the two sets of results are so close together, it would not be unreasonable to assume that the fireball temperatures will lie in the range 1100 to 1200°C.

The flames will be optically dense and behave as black body radiators giving heat fluxes in the order 200 to 270 kW/m^2 from the flame envelope. There may be additional incident heat from the non luminous combustion vapour cloud. As the emissitivity of this cloud will be between 0.1 and 0.2 it will be a second order correction to heat flux from the flame envelope.

API RP521 (15) reports that heat fluxes of 21 kW/m^2 can be sustained by humans on exposed skin for two seconds before pain is experienced. It is worth analysing this a little further in the light of two fires known to the author.

In the first, a fire in a drum store escalated over about a minute such that there were reports of the road tar melting as people evacuated nearby buildings. At this time the fire had a base of many tens of metres diameter. First and second degree burns were experienced only on exposed tissue like the back of the neck and ladies legs.

In the second fire a standby fireman operated a hand branch some 6 to 8 metres from a fire about 3 metres diameter and 6 metres height. The fire was bright and relatively smoke free. When the fire had self-extinguished some 15 minutes later, the fireman discovered his polypropylene helmet was grossly distorted due to heat radiation, but his skin and clothing were not burned.

These examples show that ordinary clothing offers a very effective protection against most burn heat radiation and should give very good protection to the body whilst making an escape.

Assuming the fireball can be approximated to a sphere and using the inverse square law relationship, the distance from the fireball centre at which a safe evacuation can be made is given by the equation below:-

$$\text{Evacuation distance} = \text{R fireball} \times \left(\frac{200}{21}\right)^{\frac{1}{2}} \text{ at } 1100^\circ\text{C}$$

$$= \text{R fireball} \times \left(\frac{270}{21}\right)^{\frac{1}{2}} \text{ at } 1200^\circ\text{C}$$

This is equal to 3.1 to 3.6 fireball radii. For a 50 tonne LPG BLEVE of diameter 110 metres this equates to an evacuation distance 170 to 200 metres.

Eisenberg (9) quotes a firemans' rule of thumb that for jumbo tankers, (assumedly of capacity about 500 tonne), 'fireman have succumbed to radiation incurred when they were as far away as 250 ft. (75m) from large fireballs'.

There is reasonable agreement between the theoretical analysis and the practical observations of the effect of BLEVES when due allowance is made for a series of extenuating circumstances, viz.

a) The likely downwind displacement of the fireball.

b) The fact that full heat flux will only be achieved after about 2 seconds when it has reached its full size.

c) The firemen will probably turn their backs to the fireball either in self protection or in evacuation.

2.4 Proposals

1. Diameter of fireball should be calculated from the following equation:

$$D = 105\left(\frac{W}{M}\right)^{\frac{1}{3}}$$

When D is the diameter in metres/W = weight of fuel in tonnes, M = molecular weight.

2. For fires on large road/rail tankers the public should be kept beyond 600m from a tanker axially and 300m sideways.

(for vertical vessels or equipment confined in heavy structures the distances may be halved).

3. The upwind evacuation distance to avoid burns = 1.5 potential diameters from the fire-seat and the down wind evacuation distance 2.5 potential diameters. For work behind fog nozzles the values could be reduced to 1.25 and 2 diameters respectively. The potential diameter is as given by equations 5 and 6.

3.0 FIRES

3.1 Appearance

The shape of pool fires is described in mathematical terms by Thomas (16) and Brown (17).

Flames in still air have a shape approximating to a cylinder. Observations on gasoline and aromatic flames suggest that the height to diameter ratio (aspect ratio) is slightly over 2 for flames of 1-m diameter to slightly less than 2 for flames fo 10-15m diameter. The work carried out by Thomas predicts that the small flames should have an aspect ratio of 3-4, this is slightly higher than is experienced in practice.

Observations on running fires suggest that the height of the flame is approximately twice the minimum horizontal dimension (not the maximum dimension).

The shape of vertical torch flames is described by Hawthorn (18) who states they have a shape approximately that of a right cone whose length is about 250 times the hole diameter and have a length:base diameter ratio to 5.3:1.

Flash fires progress across the ground at a speed of some metres per second. Any unburnt fuel either in the fuel rich zone or in the unvaporised condition may be drawn up by the rising thermal to form a fireball.

Flames from fires vary in colour. The hottest is the torch type of flame which is a white-yellow indicating temperatures of about 1300°C (confirmed by optical pyrometer). Small pool fire flames are coloured yellow to orange indicating temperatures in the range 1100°C to 900°C.

Large pool fire flames are black, sooty with small orange and red patches indicating temperatures in the range 900°C - 800°C. In general, large flames are more smokey than small flames and fuels with high carbon to hydrogen ratios tend to be more smokey than fuels with low carbon to hydrogen ratios.

Fuels with oxygen in the molecule (e.g. alcohols and ketones) tend to give less smokey flames than pure hydrocarbons.

The radiant heat flux perceived near small benzene fires tends to be higher than that for, say, gasoline fires. This is believed to be an optical density effect where the benzene flame has more carbon particles in it and tends more to a black body radiator.

A similar effect is noted on flare stacks where the unaerated flame appears to emit a relatively low level of radiant heat due to partical combustion. As the flame aeration is increased the flame temperature and radiant heat rise, (as the combustion tends to completeness), only to fall again as the flame becomes over aerated and hence cooler and less optically dense.

3.2 Radiant Heat

A number of reports have assumed that the flame temperatures should be taken as the adiabatic flame temperature. This is unnecessarily pessimistic as the total heat of combustion (total or partial) must be released as radiant heat from the surface or in the sensible heat of the products.

Simple calculations asuming that the flame has a simple geometric shape, that the fuel is consumed in stoichio-metric fuel:air ratios, that the products of combustion leaves the flame at the same temperature as the radiating surface and that the surface of the flame acts as a black body radiator show that flame temperatures should be about 1200°C - 1300°C and that about 30 - 50% of the heat should be emitted as radiant heat. These values are quite consistent with API 521 (15) and Burgess (19).

It is now worth considering the more smokey flames of interest in this paper where not all of the fuel is burnt completely some forms carbon soot and some CO, and as a result the flames are cooler.

For a fuel of composition $(CH_2)_n$ (85.7% carbon) which has a lower calorific value (LCV) of about 4530kJ/kg.

LCV carbon burning to CO	10,120 kJ/kg
LCV carbon burning to CO_2	32,770 kJ/kg
LCV hydrogen burning to H_2O vapour	120,070 kJ/kg

About 62% of the total heat of combustion is derived from burning carbon to carbon dioxide. Any partial combustion (formation of soot or CO) or over-aeration will produce a cooler flame.

There may be a risk of overestimating the heat fluxes from large pool fires if small scale data is extra-polated to large fires. Air is drawn into the flame round its base and part way up the side such that small fires with small diameters are relatively well aerated. As the size of the fire is increased, the fuel released at the centre of the pool becomes oxygen starved and will be only partially combusted producing soot and CO with a lower effective calorific value.

The correlations for mass burning rate proposed by Zabetakis (19) is based on the LCV of the fuel and on small pool fires. As the flame becomes more sooty, the effective LCV will be reduced due to partial combustion; so also should the mass burning rate. This probably reflects the change in aspect ratio predicted by Thomas (16). It would seem to be unreasonable to predict the heat fluxes based on the ideal burning rate, nor would it be reasonable to base the heat flux on the LCV.

Thring (20) reports that emissivities reach nearly unity for flames over 3m long with high carbon: hydrogen ratios. This effect is noted in API 521 (15) where the percentage heat released as radiant heat increases with size and then reaches a plateau. Does this also reflect the increase in mass burning rate with pool size noted by Zabetakis (11) in the relatively small pool burning tests where increased size in this limited range may reflect an increased radiant heat flux on the pool surface? Brown (17) suggests that the heat flux from the surface in LNG fires rises steadily to reach a maximum at about 45,000 BTU/ft^2 hr (150 KW/m^2). However when the heat flux values obtained by Burgess (19) are compared with Brown's data, there appears to be a disparity between the two results. The values of heat flux quoted by Burgess for gasoline flames shows evidence of a maximum at relatively small flame sizes (see Fig. 2).

Burgess (19) also shows that the injection of CO_2 into the flame from a fire extinguisher increases the heat flux considerably. This is as would be expected as the air entrained by the CO_2 jet would make the combustion more complete and increase the effective calorific value of the fuel. Burgess notes that 'The percentage thermal energy radiated has been as high as 34% for LNG fires - therefore it appears that all hydrocarbon fires radiated about equally at large enough diameters (compare 35 to 38% radiation for benzene'. Unfortunately, Burgess's own results for gasoline do not support this as the percentage radiation started at 30% and fell to 14% for pools of 20 ft. diameter.

It is clear that flame temperatures and heat fluxes of the large pool fires of the sort under consideration in this paper cannot be readily calculated so it is necessary once again to resort to practically derived values.

Hazagowa (3) quotes pool flame temperatures for n-pentane of 1020°C, assuming an emissivity of unity and that the non luminous radiation from the combustion gases is small, this equates to 50,300 BTU/ft^2 hr. (159 KW/m^2). Fay and Lewis (21) quote flame temperatures for unsteady burning of methane, ethane and propane flames varying between 870°C and 984°C, assuming an emissivity of unity this equates to 30,700 and 45,000 BTU/ft^2 hr., (97.2 and 142 KW/m^2).

Work carried out by the American Gas Association Project IS.3.1 estimates that the maximum radiant flux for large LNG flames is 45,000 BTU/ft^2 hr. (142 KW/m^2) giving an effective flame temperature for an emissivity of unity of 1,000°C.

Work carried out by the Fire Research Station (22) gives heat fluxes for the flame surface of medium sized pool fires up to $81m^2$ area of 38-56 KW/m^2 giving effective flame temperatures of 630-720°C.

Measurements carried out on gasoline/gas oil flames gave temperatures generally of 600°C to 800°C with a peak value of 1000°C (Private communication).

Hardee (6) quotes radiant heat fluxes for large LPG fires varying between 103 and 284 kW/m^2. Assuming emissivities of unity, this equates to flame temperatures of 915 to 1223°C. Hardee also quotes estimated heat fluxes from a torch flame of 431-489 kW/m^2 (1387-1440°C). These estimates are based on observed damage and some basic assumptions which may be in error as it has been already noted that torch flame temperatures of 1300°C have been measured by optical pyrometers.

Visual colormetric estimates of the mean effective flame temperatures and surface heat fluxes for different flames are as follows:

1300°C (350 kW/m^2) for torch flames, 1050°C (94 kW/m^2) for medium fires and 800°C (75 kW/m^2) for large smokey fires.

There is much supporting evidence to suggest that heat flux versus size curve for hydrocarbon flame, increases with size, reaches a maximum, and then falls with further size increase. The maximum heat flux may vary from one fuel to another, but should not exceed 150 kW/m^2. The size of the fire at the maximum heat flux will probably vary from one fuel to another as indicated in Figure 2.

3.3 Blast

In general the blast effects of a flash fire are localised; however, occasionally there may have been some perceptible blast.

The difference between the two extremes of localised and more perceptible blast could be due to local conditions, for example the dispersion, the delay in the ignition and the amount of fuel in the flammable zone and the degree of localised confinement of the vapour cloud.

Many reports on flash fires make no specific mention of any blast effects which suggests that they were not experienced. At Goldonna (22) only the windows of the locomotive cab very close to the release point were blown in and at Belt (11) a door was blown in about 130m from the crash site. However, very significant blasts have

been recorded as at Laurel (9) where there is report of damage to buildings from "concussion from the explosion" (which may have been the emptying tankers). At Climax (9) there is a report that an "air blast appears to have been a true detonation........". It would appear that blast cannot be totally ignored.

3.4 Extent of the Fire

Flash fires can extend over a large area as seen at Austin (9) and Belt (11). In the latter the fire is reported to have spread over 3 x $10^4 m^2$ in 2 seconds. In general it is difficult to separate what damage was caused by flash fires, what by simple radiation and what by scrub fires. Damage is, however, recorded up to 200 metres from the fire-seat.

3.5 Survival of Humans

It is most unlikely that anyone will be killed by radiation from a torch or pool fire unless of course they are trapped close to the fire-seat and the fire escalates rapidly. Any attempt to define safe distances is confused by the sensible heat received downwind of the flames which of course is significantly more than that received upwind; coupled with this of course must be the uncertainties concerning the event itself.

For normal conditions the maximum tolerable heat flux for short term exposure (about 20 seconds to burns) is 2,000 BTU/ft. hr. (6.5 kW/m^2 (15). This suggests that for a fire with surface heat flux 150 kW/m^2 it should be possible to survive without burns at least 8 fire pool diameters from the fire-seat for a flame length: diameter of 2 and 7 diameters for a flame length: diameter of 1. The significance of this should be considered in the context of large storage tanks where theoretically the distance from which fire fighting could be carried out could be exceedingly large, but where in practice fire-fighters have operated safely at less than the indicated 7 to 8 fire pool diameters. This is supporting evidence for the hypothesis that the heat flux against size plot reaches a maximum at pool sizes of about 10m and then falls with increasing size. In flash fires, humans will almost certainly be killed if enveloped in the flame as seen at Lynchburg, Belt, Eagle Pass (24, 11, 12), Austin (9) and Los Alfraque (25). The cause of death is uncertain (with the exception of Los Alfraque where death was due to burns), but it is expected that the searing heat of the products of combustion would damage both skin and lung tissue.

At Goldonna and Lynchburg (23, 24) bystanders near to, but outside the flash fire zone were burnt, but not killed. In the latter case it is possible that the burns were caused by the fireball as it rose into the sky.

A report of a fire at Donnellson (25) states that the victims lived in a house near to a pipeline leak. They may have been killed by the flash fire or burns from the torch or burns as their home was ignited by heat radiation. The report is not very specific.

A large flash fire at New Mexico (27) killed only 11 persons out of at least 123 who were in buses enveloped in the flash fire; unfortunately the cause of death was not recorded. The relatively high survival rate would be expected as the hot gases/flames should not touch the body or lung tissue.

It is concluded therefore, that houses or vehicles should provide some degree of protection against flash fires provided the fuel does not penetrate them. However, there will be a great temptation to evacuate the area and leave the protection of the building or vehicles.

3.6 Proposals

1. An experimental programme be established to ascertain the radiant heat emitted from various sized pool fires of different hydrocarbons, e.g. LNG, Gasoline, Benzene, Fuel Oil.

4.0 REPORTING

During the preparation of this paper it was noted that there were factual inconsistencies within some of the reports as well as differences in definition between reports.

It is fully recognised that the reports in question had specific objectives different from the objective of this paper, but information which was potentially useful had to be rejected on the grounds of uncertainty.

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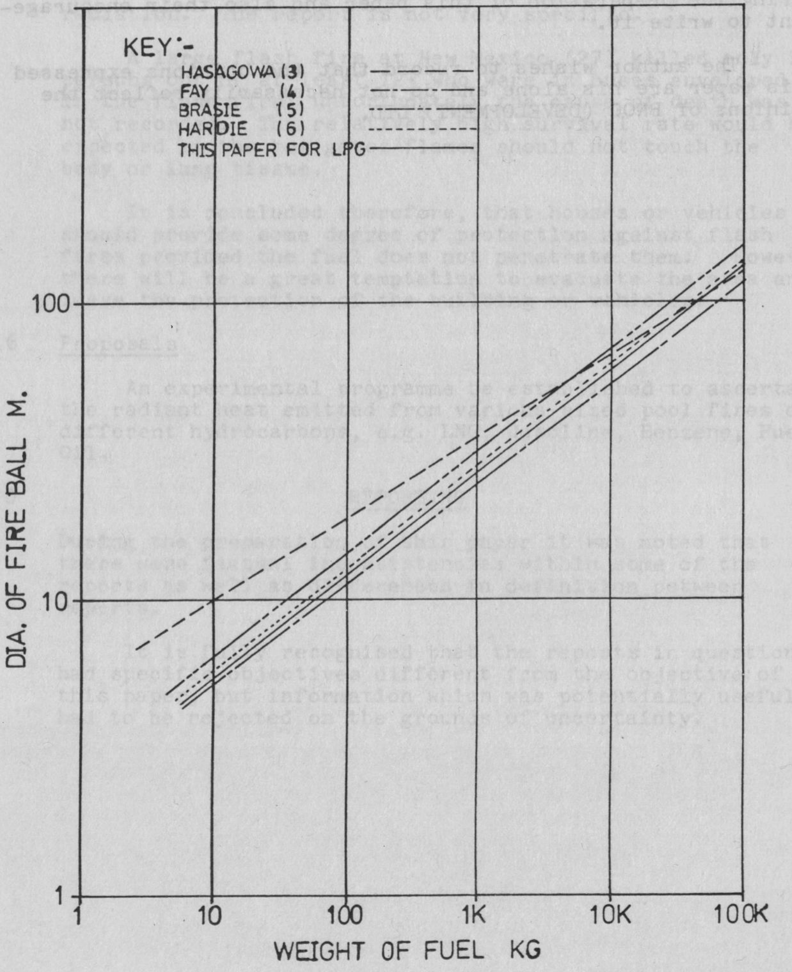

Fig. 1 Diameter of fireball for differing fuel charge and differing references

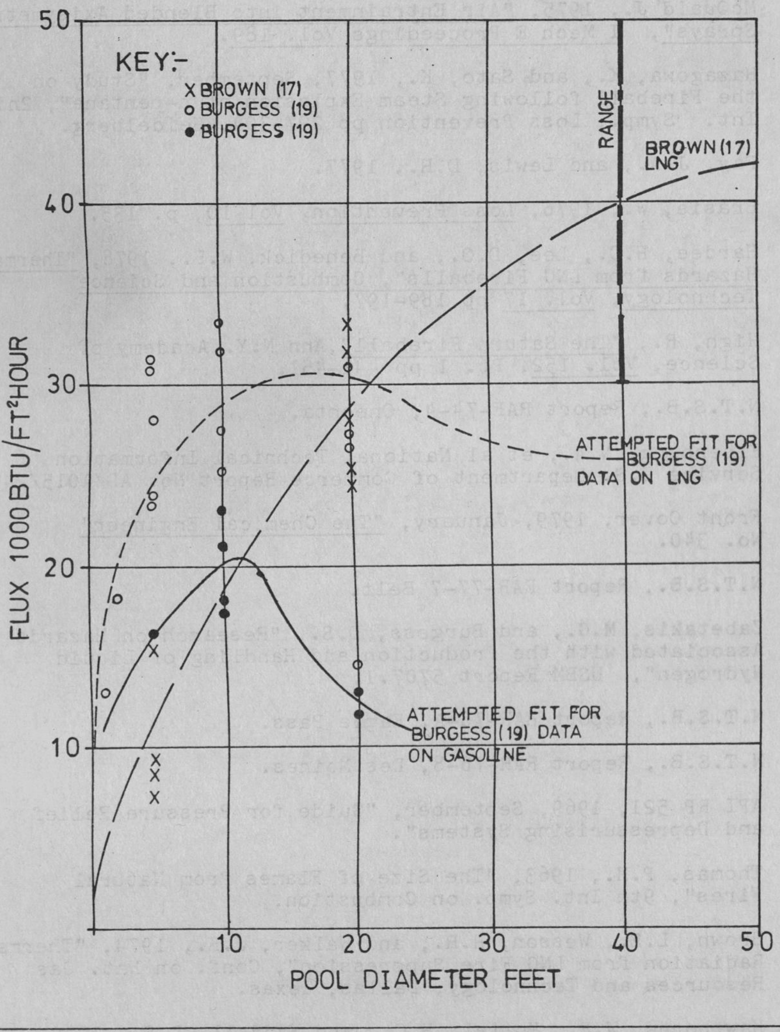

Fig. 2 Heat flux for differing LNG and gasoline pool sizes

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