THERMAL RADIATION HAZARDS FROM LARGE POOL FIRES AND FIREBALLS - A LITERATURE REVIEW

J. Moorhouse and M.J. Pritchard*

A review is presented of published data on the characteristics of large pool fires and fireballs. The relative importance of the important parameters used in calculating thermal radiation hazards is discussed and suggestions made for those areas where further information is desirable.

INTRODUCTION

A knowledge of the potential hazards from the combustion of releases of gaseous and liquid fuels is essential in order that appropriate safety measures can be adopted, and the risks to plant operators and the public can be properly assessed and minimised.

The object of this paper is to review available data on liquid hydrocarbon pool fires and on fireballs, in order that the most reliable data and calculation techniques are identified. Other reviews dealing with parts of this topic are available. Hall (1) presents a summary of primarily small scale experimental data on pool fires whilst Raj(2) considers the thermal radiation hazards from pools of liquefied natural gas.

A more fundamental review of the nature of the emission and absorption of thermal radiation by flames is presented by de Ris (3), with particular reference to burning plastic fuels and whilst this review and those by Markstein(4) and Modak(5) will in due course lead to a better understanding of the fundamental processes occurring within large flames, they are of little practical use at the present time to the engineer.

Features of fires of practical importance are the geometry, i.e. shape and size of the flame envelope, and the temperature and thermal emissive power of the flame gases.

*British Gas Corporation, Research and Development Division, Midlands Research Station, Wharf Lane, Solihull.

The shape of the flame, which is dependent upon both the source and weather conditions, is important in order to determine whether flame impingement will occur on adjacent plant or equipment. It is also an input to methods for predicting thermal radiation from a flame.

The temperature and emissivity of the flame affect the rate of heat transfer when the flame impinges on objects, as well as the radiant heat transfer to objects outside the flame.

The use of these basic parameters, the flame geometry and temperature, for determining thermal radiation hazards are discussed below. There is however one technique for determining thermal radiation hazards which does not require a detailed knowledge of these parameters, this being the point source technique.

Point Source Technique

In this technique a flame is represented as a point within which combustion of a fuel occurs. The heat radiated is considered to be a known fraction of the total heat liberated by combustion, with the heat being radiated equally in all directions.

The following equation can therefore be employed:

$$I = \frac{f m H_c}{4\pi d^2 t} \qquad \text{.............(1)}$$

The simplicity of this approach accounts for its widespread use, a noteable example being API 521 for determining hazards from venting operations. (6). It does, however, incorporate a number of assumptions. The value of f is very important and values in the range of 0.2 - 0.4 have been adopted although there is no sound reason why it should remain constant for all fire sizes and weather conditions. This shortcoming is illustrated by a heat balance on simple vertical cylindrical flame from a pool fire.

Heat radiated to surroundings = flame surface area x surface emissive power ....(2)

$$= \left(\frac{\pi D^2}{4} + \pi D L\right) . E$$

which can be equated to the fraction of the total heat liberated

$$f \dot{m} H_c . \frac{\pi D^2}{4}$$

Hence $f = \frac{E}{\dot{m} H_c}\left(1 + 4\frac{L}{D}\right)$ ....(3)

and hence for f to be a constant value, for large fires in which m and E are expected to be constant, the ratio L/D must be constant. This is not always the case as will be evident in a later section.

Two limitations of the point source technique are; firstly that receiving surfaces are always considered to be inclined towards the flame so as to receive maximum incident flux. Whilst this is sometimes true, it does

not directly predict fluxes for cases such as buildings or tanks which may have mostly horizontal and vertical surfaces.

The second limitation is that it does not allow accurate calculations to be made for objects closer than about 5 pool diameters to the fire since in this region the relative geometry of the flame and receiving surfaces becomes important. The point source technique is therefore not recommended for use in the design of protective measures close to the fuel source. The approximately spherical shape of fireballs is, however, such that a point source type approach can be a reasonable representation as is discussed below.

A technique which overcomes some of the problems of the simple point source approach is the multiple point source in which any number of discrete point sources can be adopted, each consuming a selected proportion of the fuel, and each contributing towards the radiation received by a target. This approach makes more allowance for the actual geometry of a flame and it is necessary to have a knowledge of the flame locus.

It does, however, become complex when considering the actual orientation of a receiving surface. The most suitable way of dealing with the relative orientation of the flame and a receiving surface is to consider the flame to have a solid geometrical shape.

Solid Flame Technique

The solid flame approach is a valuable technique for safety calculations since it enables all the important features of a fire to be allowed for.

The essence of the technique which has been described in detail by Raj (2) for pool fires is that a flame is considered to be represented by a solid shape which radiates heat as a consequence of its high temperature.

The thermal radiation incident upon receiving surfaces is therefore calculated from

$$I = \tau E F \qquad \text{...........(4)}$$

in which F is the geometric view factor between the flame and a receiving surface, and this approach can be adopted for all types of fires, i.e. pool fires, fireballs, jet flames. It is necessary, however, to have detailed information on the geometry and surface emissive power,E, of the flame.

A review of published information on these two items is now presented for liquid pool fires and for fireballs. Information on the atmospheric attenuation of thermal radiation which is common to both pool fires and fireballs is included in the final section of this paper.

LIQUID POOL FIRES

The parameters necessary to define the flame geometry are the flame base dimensions, flame length, flame shape, and flame tilt. In addition to a knowledge of the flame surface emissive power the other key parameter in predicting thermal radiation hazards is the fuel burning rate, since this determines the duration of the fire.

Fuel Burning Rate

Measured values of fuel burning rates for liquid pool fires of greater than 1m in diameter have been collated, and these are shown in Figure 1 for liquid natural gas (LNG), and methanol, Figure 2 for liquid petroleum gases (LPG) and liquid ethylene gases (LEG) and Figure 3 for liquid hydrocarbon fuels, as a function of equivalent circular pool diameter.

It is clearly evident for LNG and LPG that pools of a few metres in diameter do not have burning rates representative of larger pools, and this conclusion may well be valid for other hydrocarbon fuels (Fig. 3) although the scatter in the available data is quite large. No evidence has been found to equate these large variations from test to test to parameters such as wind speed.

In order to provide values of burning rate relevant to large pool fires burning rate data has been averaged for each primary fuel type for pool diameters of greater than 5m. For simple hydrocarbon fuels this correlates well with the fuel boiling point, as shown in Figure 4 and this can therefore be adopted for fuels for which no direct data exists. A universal correlation with fuel properties as proposed by Burgess and Hertzberg (7) and as shown in Figure 5 has not been obtained by the present authors.

Data for pools greater than 5m in diameter has not been found in the literature for hexane, ethylene and methanol and hence burning rate data for hexane and methanol has been included in Figures 4 and 5 solely for comparison purposes.

The surprisingly high values of burning rate available for LEG, LPG and LNG from Maezawa (8), which were obtained from pools in insulated metal pans are inconsistent with other available data and hence have not been included in the average values shown in Figures 4 and 5.

Flame Surface Emissive Power

Calculation of the radiation hazards from a flame require a flame surface emissive power, this being related to the flame temperature and emissivity by:

$$E = \epsilon \sigma T_F^4 \qquad \text{..........(5)}$$

Measurements on small pools of 0.3m diameter by Rasbash et al (9) for a range of hydrocarbon fuels gave value of T_f in the range 1260K (kerosine) to 1280K (petrol), and flame emissivities which implied that for pools above about 1 metre diameter the emissivity would equal unity.

These values, equivalent to an emissive power of about 170 kW/m^2 have been adopted by Law (10) in the design of plant safety measures, and more

recently by Robertson (11) in specifying precautions against very large hydrocarbon fires.

There is clearly a need for flame emissive power values which discriminate between different fuels and which are appropriate for large scale fires, as recently discussed by Craven (12). Only limited guidance on this topic can be provided from the literature.

In a comprehensive series of large scale experiments with aviation kerosines, JP4 and JP5, Alger et al (13) (14) (15) presented incident flux data for pools of 1, 3 and 30m in diameter. Unfortunately the data was presented as empirical equations relating incident flux to pool diameter rather than in terms of a flame surface emissive power.

Using their incident flux data, Atallah and Allan (16) made calculations of the average flame blackbody temperature by making an allowance for the temperature gradients throughout the flame. An emissive power of 47kW/m^2 was obtained. On the basis of the incident flux data as a function of distance from the fire, and the flame geometry information provided it is also possible to back calculate using view factors to obtain a flame surface emissive power. This requires assumptions regarding radiometer alignment as well as use of an appropriate atmospheric transmission coefficient, which reduces the accuracy of the approach. The values that we have obtained are shown in the following Table 1.

Table 1: Calculated Flame Emissive Powers for JP5 Pool Fires

Pool Diameter (m)	Flame Emissive Power (kW/m^2)
1	36-44
3	53-67
30	46-71

These values are generally consistent with those from the Atallah and Allan approach.

A similar value, 60 kW/m^2, was obtained by Hagglund and Persson (52) for a 10m diameter kerosine fire, whilst a 2m diameter pool fire had a maximum surface emissive power of 130 kW/m^2.

Measurements on a 1m diameter pool of pentane by Hasegawa and Sato (17) resulted in a surface emissive power of 61 kW/m^2.

It is evident therefore that values of flame surface emissive power greater than 100 kW/m^2 may be relevant for some liquid hydrocarbon pool fires in small diameter pools. For large diameter pools, values are unlikely to exceed about 60 kW/m^2. The use of values such as 170 kW/m^2, based on laboratory scale experiments is therefore not appropriate.

For liquefied hydrocarbons, i.e. LNG, LPG, and LEG, a direct comparison between the radiative output of 2.65m square pool fires was obtained by Maezawa from incident flux measurement at a distance of 5½ pool diameters.

His incident flux values were:

LNG 1.51 kW/m^2
LPG 1.98
LEG 2.68

The incident flux value for LEG is confirmed by that of Sheldon (18), who obtained a value of $2.7kW/m^2$ at a distance of 5½ pool diameter from a 3m diameter circular pool.

Although the burning rates in Maezawa's experiments were higher than expected for steady state fires, it can be inferred from these fluxes that LPG and LEG fires represent a more severe fire hazard than that posed by LNG. It is desirable to examine whether this conclusion is valid for fires of larger diameter. Unfortunately, no data have been found in the literature for larger LPG or LEG fires. There is, however, substantial data for LNG fires from Lehrer (19), Japan Gas (20), Atallah and Raj (21) (22), and Raj eta al (2).

This data is summarised in Figure 6 along with emissive power values for other fuels, as a function of pool diameter. For LNG fires the only obvious inconsistency in the observed trend of increasing emissive power with diameter up to a maximum value is that for the 24m diameter fire. For this test it is recognised that due to experimental difficulties it can only be regarded as a minimum value.

The recent large scale data (24) for pools of up to 15m diameter, obtained by spilling LNG onto water demonstrates that for this fuel, a fire approaching optical thickness is not achieved until the flame is many metres thick. These small fires do, however, burn with a particularly clean flame, with evidence of soot formation only when pools are of the order of 10m diameter, or when the majority of the fuel has been consumed such that only the heavier hydrocarbon components remain. This is in marked contrast to the higher hydrocarbon fuels which produce large volumes of soot. In pools of a few metres in diameter, fuels such as LEG produce flames which are very similar to those of LNG, whilst the behaviour on a larger scale has not yet been examined.

An accurate knowledge of the average flame emissive power is essential for calculation of thermal radiation hazards, but in some situations a knowledge of variations over the surface of a flame can be important. If the base of a flame is less emissive than the average for the flame as a whole (5), due for example to the presence of cold absorbing fuel vapours and their decomposition products then this can be important in assessing plant safety measures. This is a topic which has not yet received detailed study on large scale fires although narrow angle radiometer measurements on LNG flames (2) have indicated that such effects can be significant.

Flame Geometry

The primary geometrical parameters necessary to define a flame from a pool are the flame length and its orientation to the vertical. In order to represent the flame as a continuous surface it is also necessary to approximate the flame shape to a simple geometrical shape and a cylinder is normally chosen for this purpose.

Various studies have measured these geometrical parameters and provided relationships between them and the pool diameter, fuel burning rate, and local weather conditions.

Flame Length

Experimental studies of wooden crib fires were used by Thomas to validate equations developed to predict flame lengths under calm (22) and wind blown conditions (23). These equations are frequently used as a means of determining flame length, measured along the axis of the flame, as a function of pool diameter and fuel burning rate for other fuels. It is instructive therefore to compare available experimental data with the Thomas equations.

Data for kerosene, diesel and gasoline is shown in Figure 7 from the predicted trends alongside the Thomas equations and it is clear that the data departs considerably from the predicted trends. (The Thomas equation for wind blown flames has been presented in Figures 7 and 8 for a value of wind speed of 5m/s in order to demonstrate the degree of flame shortening predicted by the equations.) The dimensionless flame length tends towards a constant value of 1.7 at large pool diameters this being consistent with the predictions by Brötz (53) using a simple dispersion technique.

More comprehensive data for flame length is available for LNG fires as shown in Figure 8. Some of the data is for spills onto land, and some for spills onto the sea which resulted in a burning rate greater than that induced by the back radiation from the flame alone. Clearly the Thomas equation for calm wind conditions might be regarded as the most appropriate but there are considerable deviations from this.

A possible explanation is that the equations do not make proper allowance for the influence of the wind on the flames. An examination has therefore been made using the data of the influence of wind speed on flame length but no obvious dependence has been obtained.

On the basis of the data for both large LNG and large liquid hydrocarbon fuel fires it can be inferred that the Thomas equations are unlikely to provide an accurate guide to the length of flames on pool of diameter greater than about 25m for LNG fires and 40m for hydrocarbon fires. More reliable assessments may be made from the available large scale experimental data.

Flame Tilt

A knowledge of flame tilt is important when predicting incident flux levels at positions close to a fire since it can markedly affect the distance between the flame and a receiving surface. At remote positions from the flame a tilted flame will appear to be shorter and hence underestimates of flame tilt angle can result in pessimistic hazard distances.

Data on the influence of wind on the flame tilt angle is available for large LNG (21) and JP5 pool fires (13)

On the basis of flame tilt data for a 10.6 x 19.8m JP5 pool fire, the value of the constant A in the equation

$$\frac{\tan \theta}{\cos \theta} = \frac{A U^2}{D} \quad \text{........(6)}$$

was determined, this equation being of the form of that developed by Welker and Sliepcevitch (25) from small pool fire experiments in wind tunnels.

The detailed data obtained for LNG fires which is shown in Figure 9, is expressed in terms of the equation

$$\cos \theta = \frac{0.75}{U^{*0.49}} \quad \text{.....(7)}$$

which was developed by Thomas (23).

The equation developed for JP-5 fires has also been included in Figure 9. It is clear firstly that there is considerable variation from test to test in the observed flame tilt, and secondly that the degree of tilt is greater for the LNG fires. This latter conclusion is surprising since the hotter and hence more buoyant LNG fires would be expected to be less influenced by the wind.

Although the degree of variation in the data for LNG fires is quite large, it represents the best available for use in hazard calculations and if used for fuels other than LNG it is unlikely to lead to large errors.

Flame Drag

Observations on small flames in wind tunnels, intended to simulate liquid pool fires (25) have demonstrated the tendency of the base of the flame to extend downwind outside of the confines of the liquid pool. This phenomenon is termed flame trailing or flame drag and has also been observed in small scale experiments in which the rims of the pools have been flush with the ground.

This behaviour has also been observed in large scale JP-5 pool fires (13) but has not been quantified, although Robertson (11) has indicated that the flame base extension can be as much as 50% of the pool diameter. The scaling relationships developed on the basis of small scale pools, by Welker and Sliepcevitch (25) for a wide range of fuels suggests that the flame drag will be significantly greater than this.

Until detailed data relevant to a larger scale is available it is not possible to determine whether it represents an important feature in selecting an appropriate flame shape and hence in predicting thermal radiation hazards.

Geometric View Factors

Geometric view factors between the flame surface and selected targets can be calculated using standard published techniques (2) (34) although for cases in which the flame departs from a simple geometrical shape it is necessary to resort to dividing the flame into a number of increments. Whilst this latter technique is more demanding it is more flexible. It allows variations in emissive characteristics over the flame surface to be introduced as well as a more rigorous allowance for the distance between

each part of a flame and a receiver when determining the degree of absorption of radiation by the atmosphere.

In selecting a shape by which to characterise the flame it should be recognised that a flame defined by a cylinder of length equal to the flame length, can overestimate the actual area of the flame. Brotz (54) has quantified this for small pool fires and has estimated that it can overestimate by as much as 20%. This can represent a safety factor in hazard calculations.

Unsteady Fires

Continuous spills of flammable liquids onto unbounded surfaces on land or sea upon ignition will result in a pool which spreads until the rate of fuel supply is matched by the rate of consumption. In the specific case of spills of cryogenic fuels then the rate of vaporisation of the fuel will be the sum of that due to the fire plus that due to heat transfer from the land or water into the fuel.

The only large scale data available for such unsteady state fires is that by Raj (24) for LNG spills onto water and this has already been examined above.

In calculating thermal radiation hazards from a spreading pool fire it is necessary to consider the fire as represented by a series of steady state fires, using appropriate values of pool diameter and fuel consumption rate (37). This allows incident flux to be integrated over the duration of a fire.

Slot or Channel Fires

The previous sections have considered the behaviour of fires burning in circular, square or near square pools. Fires in pools of large length/width ratio such as spillage catchment pits (40), might be expected to exhibit many similar characteristics, but it is not necessarily valid to apply the same relationships. A useful approach for calculation purposes, is to assume that a slot fire can be split into a series of individual pools and then apply available relationships for near circular pools. The small scale experimental studies on slot fires (38) (39) have indicated that this approach is valid although no large scale verification is as yet available. Alger and Capener (13) have however reported some large scale burning rate data for JP-5 fires, for pools of length/width ratio of greater than 2/1. This data represented in the form described above in Figure 3, is consistent with that from circular or near circular pools.

FIREBALLS

The rapid combustion of flammable vapour in a spherical envelope is generally termed a fireball. The strong buoyancy forces of the hot combusting gases result in turbulent mixing and the formation of a mushroom shaped cloud, often with a 'stem' of flame emanating from the source of the fuel. It is the high degree of turbulent mixing, and rapid air entrainment which allows large quantities of fuel to be consumed in a short period.

Large quantities of heat are radiated from the hot mass of combusting gases and it is the high radiant flux levels which represent the major hazard from fireballs, extending well beyond the region that the flame envelops.

Fortunately combustible materials such as wood require not only very high flux levels to cause spontaneous ignition, but also extended exposure periods before ignition occurs (41). On the other hand, people are more susceptible to incident thermal radiation, particularly from short intense exposures since the blood supply has inadequate time to contribute to the cooling of the skin (42),(43),(44).

It is important to have a detailed understanding of the fireball process in order that the thermal radiation hazards from such events can be properly quantified, and so that any practicable measures can be taken to reduce the causes and the consequences.

Fireball Incidents

A number of accidents have occurred leading to a fireball, and these have involved the rapid release of the contents from pressurised rail and road tankers containing hydrocarbon fuels. These failures have occurred due to mechanical damage, or fire induced failure due to overheating resulting in a BLEVE (Boiling Liquid Expanding Vapour Explosion).

A list of incidents for which quantitative data is available is shown in Table 2, together with the source of that information. The data on fireball diameter is primarily from eye witness reports, and hence can be subject to large errors. Nonetheless it is still valuable as will be shown below in relation to data from small scale experiments.

Incidents leading to fireballs have also occurred in rocket launch pad accidents (45),(46),(47).

Experimental Studies

In determining the thermal radiation hazard presented by fireballs there are four primary parameters which are relevant:- the mass of fuel involved, the fireball diameter, the duration, and the surface thermal emissive power. From a knowledge of these, simple estimates of the radiation hazards from fireballs using point source type techniques can be made.

For more detailed calculations additional information is required including a knowledge of the change in diameter with time, the vertical rise of the fireball, and the variation in emissive power during the lifetime of the fireball.

Fireball Diameter

Experimental studies of fireballs have been carried out with small quantities of quiescent gaseous fuels contained in soap bubbles, Fay and Lewis (49), and balloons and plastic bags, Hardee et al (48), with

hydrocarbon fuels in quantities up to 10kg. The relationships which have been obtained to relate maximum diameter with fuel mass are summarised in Table 3. Studies with fuel quantities from 0.3 up to 31kg have been carried out by Hasegawa and Sato (17) (50) in which the fuel was rapidly released from a vessel after superheating to a selected pressure.

The difference between the various relationships developed to predict fireball diameter is small. The value of the exponent in the equations is generally about $^1/_3$, although for those experiments in which the fuel was not released under pressure the values are slightly larger. The 0.33 exponent presented by Fay and Lewis was derived theoretically and not from a mathematical fit to the data. There are no obvious differences between the fuels examined and this presumably reflects the fact that a unit mass of most hydrocarbon fuels requires a similar volume of air for complete combustion.

The data presented by Hasegawa and Sato (50) for tests involving fuel masses in the range 3 to 31 kg has been correlated by the present authors using a computer curve fitting technique and the following relationship has been obtained

$$D_{MAX} = 5.33\, m^{0.327} \qquad \text{.............(8)}$$

this being slightly different from the authors' original equation which was derived using the data from all tests involving fuel masses in the range 0.3 to 31kg.

The good general agreement on the dependence of maximum diameter on fuel mass is shown in Figure 10, the range of experimental data being indicated by the solid lines on the graph. The small differences in the equation do, however become magnified if the relationships are extended to much larger fuel masses as shown in Figure 11. The data available from incidents is also shown in this Figure and it is particularly valuable in selecting an appropriate relationship for use.

It is clear that equation 8 is in better agreement with the other relationships than Hasegawa and Sato's own equations.

Additional verification of this general agreement is provided by the experiments and rocket abort incidents with rocket propellant/oxygen mixtures for fuel masses in the range 1 to 100,000 kg, indicating the validity of scaling over a very large mass range and the lack of any strong dependence on fuel type. It is noteworthy however that from these results the variations from test to test were large, being of the order of 30%.

This good scaling over a large mass range provides valuable support to the theoretical equation developed by Fay and Lewis (49) which assumes that the rate of combustion is determined by the rate of air entrainment over the whole of the fireball surface, this being in direct proportion to the rate at which the fireball is rising. The upward motion is obtained by equating the rate of change of vertical momentum to the buoyancy of the fireball.

In determining the buoyancy no allowance is made for any heat radiated by the fireball.

The relationship proposed by Hardee et al (48) is also derived theoretically, and it is evident that fireball diameters determined by Fay and Lewis for pure vapour fireballs are similar to those predicted by Hardee for premixed fuel/air fireballs. This is consistent with the knowledge that the resultant diameter upon combustion of a given quantity of fuel is relatively insensitive to the fuel/air ratio.

Fireball Duration

Whilst there is fairly good agreement between the equations developed for the maximum fireball diameter between the various workers, this agreement is not evident for measurements of fireball duration. This can be partly attributed to the way in which the duration is defined by different researchers. The important phases are illustrated in Figure 12. A fireball grows until it starts to lift off the ground, this lift off time generally coinciding with the attainment of the maximum diameter. The fireball then persists until the fuel is completely consumed, shortly after which the visible fireball disappears.

A summary of the equations relating fuel mass and fireball duration are included in Table 3, and presented graphically in Figure 13. Fay's data is for 'complete combustion' of the fuel and the Gayle and Bransford data is the 'time for the visible fireball to disappear'. These would be expected to be physically similar. On this scale the combustion times for the rocket fuel/oxygen mixtures do not appear to be representative of hydrocarbon fireballs.

Hasegawa and Sato defined an effective fireball duration as the time for which the fireball area exceeded half the maximum value, and hence obtained lower values than other workers. This approach does have some merit when calculating hazards from fireballs, since it gives a more accurate assessment of the total incident flux than techniques which assume a fireball of constant maximum diameter.

The data presented by Hardee et al (48) is for the combustion time up until the fireball starts to lift off the ground. He suggests that the total combustion time will be about twice the lift-off time, and this is reasonably consistent with the total duration data presented by Fay and Lewis.

The detailed data presented by Hasegawa and Sato allows correlations to be made on their larger scale tests rather than include the very small test masses. We have therefore developed the following equations for effective duration, t_a and total duration t_{tot},

$$t_a = 0.923\ m^{0.303} \quad \text{...(9)}$$

and $$t_{tot} = 1.089\ m^{0.327} \quad \text{...................................(10)}$$

these being based on data from 37 separate tests.

It is evident that the authors' original equations are significantly affected by the data on small masses. Our equations highlight the degree of pessimism introduced if thermal radiation calculations are based upon the total duration, and also show the better agreement with other relationships when extrapolated to larger fuel masses as shown in Figure 14.

The relationship between fireball duration and fuel mass can therefore be seen to have an approximately $^1/_3$ power dependence for the two sets

of experiments in which fuel was released under pressure (45) (50), and a $^1/_6$ power dependence for experiments involving small masses of fuel and fuel/air mixtures contained in balloons and plastic bags.

It might have been expected that fireball durations would be greater in situations where turbulent mixing induced by a high pressure source is absent, but this is not substantiated by the available data.

The difference between the exponents obtained may well be explained by the scale of the experiments, small scale studies on quiescent fireballs by Fay and pressurised fuels by Hasegawa and Sato both show low values. This implies that very small scale laboratory fireballs do not provide an accurate guide to the duration of larger scale events.

In calculating hazards, no data has been obtained from incidents which could help to determine which relationship is most valid. The only large scale data is that from the rocket fuel/oxygen fireballs, and even though somewhat different from hydrocarbon/air fireballs, the Gayle and Bransford relationship is probably the most relevant equation for use at the present until large scale hydrocarbon fireball experiments are undertaken.

Fuel Quantity

Theoretical and experimental studies have clearly highlighted the importance of the mass of the fuel involved in a fireball. There is unfortunately very little quantitative information on the proportion of a release which is actually consumed within the fireball.

Hasegawa and Sato observed some dependence upon the quantity of superheated fuel expected to flash into vapour. In the small scale experiments with up to 10kg of fuel, a flash contribution of greater than 36% resulted in all the fuel being consumed within the fireball. When between 20 and 36% flashed-off, part of the fuel was consumed as a liquid pool fire, and for less than 20% a large majority of the fuel burnt on the ground in a pool.

In pressure vessel depressurisation experiments with ethylene (18) it was concluded that about half of the fuel within the vessel contributed to the fireball.

When calculating hazards from fireballs it is not uncommon (48) (51) for the whole of the contents of a pressure vessel to be assumed to be involved in the fireball. Whilst this may be sometimes relevant it is not necessarily always the case and therefore can lead to a high degree of pessimism in safety calculations. The minimum quantity for calculation purposes would be the flash contribution alone. The manner of vessel failure will undoubtedly have a bearing upon any additional contribution. Some liquid will be entrained into the flashing vapour as droplets, but in cases where the vessel contents are discharged onto the ground rather than projected into the air, a pool fire would be expected to result as has been observed on the small scale (17).

On the basis of the limited experimental data it is not possible to recommend definitive guidance on this important aspect of fireballs. For calculation purposes, an approach which is unlikely to result in an underestimation of thermal radiation hazards is to use a fuel mass which includes an amount of entrained liquid equal to the quantity of liquid which flashes to vapour, and to use the total fuel mass when the flash contribution is greater than 36%.

Fireball Emissive Power

Information in the literature on fireball thermal emissive power is very limited, and this is summarised in Table 3, and shown as a function of fireball maximum diameter in Figure 15.

The adiabatic flame-temperature obtained by High (47) with rocket propellant/oxygen mixtures is clearly not relevant to hydrocarbon fireballs, although similar values have been erroneously adopted for hazard studies (54) for propane fireballs.

For stoichiometric methane/air fireballs Hardee et al (48) measured an emissive power of 123 kW/m^2 for an optical path length of 1.67m, and this compares reasonably well with 160 kW/m^2 calculated from Hottels charts (55). For larger fireballs Hardee proposed use of the equation:

$$E = E_{max} (1-e^{-bD}) \qquad (11)$$

with a value of b derived from large LNG pool fire experiments (21), and thus obtained a value of E_{max} of 469 kW/m^2, which he proposed as an upper limit for fuel/air fireballs.

For pure fuel fireballs Fay and Lewis obtained values of 32kW/m^2 (methane), 21kW/m^2 (ethane) and 52kW/m^2 (propane) for fuel masses up to 0.1kg.

Values relevant to larger fuel masses have been obtained by Hasegawa and Sato, and these are shown in terms of maximum fireball diameter in Figure 15. In most of the experiments the emissive power increased as the fireball expanded and subsequently decayed, although in some tests the value rose to a maximum at extinction. There is significant variation from test to test and this may well be attributable to the effect of wind which causes considerable alterations in fireball behaviour. If this hypothesis is correct, with the knowledge that wind effects can induce enhanced mixing of fuel and air then emissive powers may be expected to approach the values relevant to premixed fuel/air fireballs proposed by Hardee. It is evident from Figure 15 that this is a plausible explanation for the high values of emissive power obtained. This potential enhancement of emissive powers would not be expected to be as important for fireballs involving much larger fuel masses.

It is not obvious from the Hasegawa and Sato paper whether allowance has been made for atmospheric attenuation of radiation between source and receiver when deriving these values of source emissive power. This could serve to increase the values by as much as 40% for cases in which measurements were made at distances of 66m.

One of the variables in the experiments was the initial fuel pressure and the data in Figure 15 is shown in terms of 4 pressure ranges, which suggests a possible pressure dependence. Although there is considerable spread in the data the present authors have derived a correlation as follows:

$$E = 235 P^{0.39}, \text{ for fuel masses of 6.2kg} \qquad (12)$$

It is not possible to determine the importance of source pressure for larger fuel masses from the data presented.

For calculation purposes for pure vapour fireballs, it is not possible on the basis of available data to select accurate values. A realistic minimum is about 150kW/m^2 based on values from Hasegawa and Sato and the maximum value is unlikely to exceed 300kW/m^2.

For more detailed calculations a knowledge of the variation in emissive power during the lifetime of the fireball is required (56).

Fireball Growth

Experimental studies have shown the growth in a fireball is rapid. The rate of expansion for an unignited release from a pressure vessel has been examined by Hardee and Lee (58).

A theoretical analysis based on the conservation of the source momentum predicts that diameter increases in proportion to $t^{1/3}$, and has shown that this is consistent with experiments in which up to 440kg of volatile hydrocarbon fuels were released. A similar dependence was derived by Bader et al (59) with the assumption that there was a constant rate of fuel addition to the burning cloud, and no air entrainment. This relationship which was substantiated by large scale fuel/oxygen experiments has been adapted by Hardee et al for their model of a fuel/air fireball.

For pure vapour fireballs, Fay and Lewis derived a relationship which predicts that the fireball radius is proportional to t^2. This is based upon a buoyant mixing model in which the combustion is mixing controlled. Their small scale experimental measurements do not support this relationship (56), and lead to diameter being proportional to t^x in which X = 0.84 (methane), 0.77 (ethane), and 1.12 (propane).

The Hasegawo and Sato data provides detailed data for fireball area (and hence equivalent diameter) as a function of time and an examination of selected tests suggests an expansion rate proportional to t^n where n is not less than $^1/_3$. No clear trend emerges from the data since there are changes in the rate of expansion during the growth period.

If calculations are to be made utilising the growth of a fireball then on the basis of the evidence it is most appropriate to assume a $^1/_3$ power dependence for all cases until more consistent data is available.

Fireball Rise

Upon reaching a diameter close to the maximum diameter, large scale fireballs have been observed to rise from the ground. A summary of the limited available data is included in Table 3.

In general the height that the centre of the fireball rises to is approximately equivalent to the maximum fireball diameter, although the data for large scale rocket fuel incidents suggests that this rise height can be considerably larger.

Calculation Techniques for Determining Hazard Distances

Use has already been made of a point source technique for assessing the importance of fireball parameters, and this utilises the assumption that a fixed fraction of the heat of combustion is radiated as given in equation 1.

This equation, which neglects attenuation of radiation by the atmosphere, assumes that any receiving surface is inclined to receive maximum flux levels, and avoids any detailed knowledge of the fireball geometry.

Since

$$I\,4\pi d^2 = E\pi D^2 \qquad \text{...........(13)}$$

then

$$f = \frac{\pi D^2 E t}{m H_c} \qquad \text{...........(14)}$$

If the relationships for $D \propto m^{1/3}$,and $t \propto m^{1/3}$ are substituted into this equation then

$$f = \frac{\pi E}{H_c} \qquad \text{...........(15)}$$

which states that for fireballs which have reached such a diameter that the surface emissive power is independent of diameter the fraction of heat radiated is constant.

The danger of using a point source approach with a constant value of f with an inappropriately short fireball duration (51) is that for large fuel masses, a simple thermodynamic balance on the flame can be violated and fireball temperatures can be predicted which are in excess of adiabatic flame temperatures.

For hazard calculations the distance along the ground from an item of plant is of more relevance than the distance from a receiver to the centre of the fireball.

For a fireball with its edge in contact with the ground,the ground or 'stand-off' distance S is given by:

$$d^2 = S^2 + \left(\frac{D}{2}\right)^2 \qquad \text{...........(16)}$$

and hence equation 13 becomes:

$$\frac{I}{E} = \frac{D^2}{4S^2 + D^2} \qquad \text{...........(17)}$$

which can be expressed as (60),

$$I = \frac{\tau E \dfrac{D^2}{S^2}}{4 + \dfrac{D^2}{S^2}} \qquad \text{...........(18)}$$

in which τ is evaluated for the distance from the fireball surface to the receiver.

The availability of reliable relationships for the expansion and vertical rise of fireballs, and a more accurate knowledge of the variation of emissive power with time are the keys to developing more accurate calculation techniques. These can only serve to reduce the pessimism in the simple techniques which use maximum fireball diameters and maximum emissive powers for the whole duration of fireballs located at ground level.

ATMOSPHERIC ABSORPTION OF THERMAL RADIATION

Accurate calculation of the thermal radiation incident upon a receiving surface requires a knowledge of the degree of attenuation of the radiation by the atmosphere between the flame and the receiver. This is a requirement common to both pool fires and fireballs.

The attenuation by the atmosphere occurs primarily due to absorption by constituent gases, and to a lesser extent due to scattering by suspended dust and aerosol particles. On a clear day this latter aspect can be ignored.

Carbon dioxide and water vapour are the principal molecular absorbing species, the degree of absorption being a function of the partial pressure, total pressure, and temperature. Much work has been carried out on the determination of absorption coefficients and a comprehensive set of data at $0.1\mu m$ intervals, over the spectral range $0.3 - 14.0\mu m$ has been presented by Hudson (61) for a wide range of absorber concentrations. Similar, although less extensive data may be obtained from Kruse (62), Kondratyev (63) Ludwig (64), and Wyatt et al (65).

Calculation of the total absorption therefore requires the integration of the proportion absorbed over each wave length interval from a knowledge of the absorber partial pressures, and the emission spectrum of the radiating source.

Unfortunately, accurate emission spectra for large fires and fireballs are not available and it is therefore necessary to resort to the assumption that the fire is a black body emitter at an appropriate temperature. Absorption calculations are therefore rendered straightforward, but tedious, and this assumption is likely to be realistic for large sooty flames. It will not be realistic for emission from premixed fuel/air flames, and these can be treated in the manner described by Hardee et al, since no attempts have yet been made to measure emission spectra from pure fuel fireballs.

There are, however, two sources of information for the emission spectra of large LNG fires (21), (24) and both illustrate the difficulties in obtaining useful data. In both cases the spectral wavelength region scanned by the spectrometer only accounted for about 75% of the thermal energy radiated, thus necessitating corrections for the remaining 25%. In addition the measurements, which showed that LNG fires emitted preferentially at certain wavelengths, were made at large distances from the fire. The spectrum obtained was therefore subject to considerable absorption by the atmosphere and since at some wavelengths total absorption had occurred it was not possible to back calculate to the spectra at the surface of the flame.

Emission spectra at the flames' surface are therefore required in order to perform the most reliable calculations and ideally it is desirable to know the variation over the surface. Until such time as this ideal is achieved recourse must be made to the assumption of a black body source.

Safety calculations require a transmission, rather than an attenuation coefficient and results of typical transmission coefficients as a function of distance are shown in Figure 16 for a black body source temperature of 1150K. The air Relative Humidity is clearly an important parameter and over the range of temperatures relevant to pool fires and vapour fireballs it is more important than variations in source temperature.

Comparison is also shown with the degree of attenuation obtained for thermal radiation emitted from nuclear explosions (75) and is evident that use of this type of relationship is not appropriate, being relevant to very much higher source temperatures than from combustion events.

For hazard calculations atmospheric transmission coefficients appropriate to the type of combustion event considered should therefore be adopted, and the path length chosen for absorption should be representative of that from the receiver to the flame surface and not based upon the ground separation distance.

CONCLUSIONS

The scientific literature relevant to pool fires of hydrocarbon liquids, and fireballs following failure of pressurised stores has been reviewed. Data and relationships are proposed which are believed to provide the best estimates of the potential thermal radiation hazards.

In some cases conservative assumptions are incorporated thus leading to possible overestimates of thermal radiation hazards, and in order to prevent this, parameters have been identified for which further information is necessary.

SYMBOLS USED

A = constant

b = extinction coefficient (m^{-1})

D = diameter (m)

D_{MAX} = maximum fireball diameter (m)

d = distance from flame or fireball centre to receiving surface (m)

E = flame surface emissive power (kW/m^2)

E_{MAX} = maximum emissive power (kW/m^2)

f = fraction of heat of combustion of fuel which is radiated

F = view factor between flame and receiving surface

g = gravitational constant (m/s^2)

H_c = heat of combustion (kJ/Kg)

H_v = heat of vaporisation (kJ/kg)

I = intensity of incident thermal radiation (kW/m^2)

L = flame length (m)

m = mass of fuel (Kg)

$\dot{m}$ = fuel burning rate (kg/m^2s)

P = source pressure (MPa)

S = stand off distance measured along the ground (m)

t = time (s)

t_a = effective fireball duration based upon observed fireball area (s)

t_b = time to complete combustion of fuel in a fireball (s)

t_L = fireball lift-off time (s)

t_{tot} = total fireball duration (s)

T_f = flame temperature (K)

U = wind speed (m/s)

U^* = dimensionless wind speed

X = constant

ϵ = flame emissivity

σ = Stephan Boltzman constant ($kW/m^2\ K^4$)

τ = atmospheric transmission coefficient

θ = angle of flame tilt from vertical, (degrees)

ρ_a = air density (kg/m^3)

REFERENCES

1. Hall, A.R., 1972, "Pool Burning - A Review", Rocket Propulsion Establishment, Tech. Report 72/11.

2. Raj, P.P.K., 1977, AGA Transmission Conference, St. Louis, Missouri, U.S.A.

3. de Ris, J., 1978, "Fire Radiation - A Review". Factory Mutual Research Corp. OAOE6. BU-2.

4. Markstein, G.H., 1976, Combustion and Flame, 27, 51.

5. Modak, A.T., 1981, Fire Safety Journal,3,177.

6. American Petroleum Institute, 1969, Report API 521, "Guide for pressure relief and depressurising systems".

7. Burgess, D.S., and Hertzberg, M., 1974, Advances in Thermal Engineering, Chapter 27, 413. John Wiley and Sons.

8. Maezewa, M., 1973, Japan Society for Safety Engineering "Experiments on Fire Hazards of Liquefied Flammable Gases".

9. Rasbash, D.J., Rogowski, Z.W., Stark, G.W.P., 1956, Fuel, 35 (1), 94.

10. Law, M., 1969, Building,29, 86.

11. Robertson, R.B., 1976, The Institution of Chemical Engineers, Process Industry Hazards, Symposium Series No. 47, 157.

12. Craven, A.D., 1976, The Institution of Chemical Engineers, Process Industry Hazards, Symposium Series No. 47, 39.

13. Alger, R.S., and Capener, E.L., 1972, "Aircraft Ground Fire Suppression and Rescue Systems - Basic Relationships in Military Fires - Phases I and II". US Naval Ordinance Laboratory, Maryland, AGFSRS-72-1.

14. Alger, R.S. et al. 1975, "Aircraft Ground Fire Suppression and Rescue Systems, Phases III, V, VI and VIII". Naval Surface Weapons Center, DOD-AGFSRS-75-4.

15. Alger, R.S. et al, 1975, "Aircraft Ground Fire Suppression and Rescue Systems, Phase IV" Naval Surface Weapons Center, Maryland, DOD-AGFSRS-75-3.

16. Atallah, S., and Allan, D.S., 1971, Fire Technology, 7, 1, 47.

17. Hasegawa, K., and Sato, K., 1977, Proceedings of the 2nd International Symposium on Loss Prevention. Heidelberg, 297.

18. Sheldon, M., (translator) 1977 "A Report on the Experimental Results of Explosions and Fires of Liquid Ethylene Facilities" Institution for Safety of High Pressure Gas Engineering, Tokyo.

19. Lehrer, P., 1973, Gas und Wasserfach, 114, (7), 340.

20. Japan Gas Association, 1976, "A Study of Dispersion of Evaporated Gas and Ignition of LNG Pool Resulted from Continuous Spillage of LNG Conducted During 1975".

21. American Gas Association, 1974, "LNG Safety Program - Interim Report on Phase II Work", Report No. IS-3.1.

22. Thomas, P.H., 1963, 9th Symposium (International) on Combustion, Academic Press, New York.

23. Thomas, P.H., 1965, Fire Research Note No. 600, Fire Research Station.

24. Raj, P.P.K., Moussa, A.N., and Aravamudan, K., 1979, U.S. Coast Guard Report No. CG-D-55-79.

25. Welker, J.R., and Sliepcevich, C.M., 1966, Fire Technology,2,(2) 127.

26. Blinov, V.I., and Khudiakov, G.N., 1957, Academiia Nauk, SSSR Doklady, 113, 1094. (Hottell, H.C., 1958, Fire Research Abstracts and Reviews, 1, 41).

27. Burgess, D.S., and Zabetakis, M.G., 1962, U.S. Bureau of Mines Report No. 6099.

28. Burgess, D.S., Strasser, A., and Grumer, J., (1961) Fire Research Abstracts and Reviews, 3, 177.

29. Wood, B.D. and Blackshear, P.L., 1969, "Some observations on the mode of Burning of a 1½m Diameter Pan of Fuel", Combustion Laboratory Tech. Report No. 7, University of Minnesota.

30. Johnson, D.W., et al., 1980, "Control and Extinguishment of LPG Fires" U.S. Department of Energy, Report No. DOE/EV-6020-1.

31. Yumoto, T., 1971, Combustion and Flame, 17, 108.

32. Pavlov, P.P., and Khovanova, A.M., 1959, Fire Research Abstracts and Reviews, 1, 53. (Review by Johnson, O.W.).

33. Alger, R.S., Corlett, R.C., Gordon, A.S., and Williams, F.A., 1979, Fire Technology, 15, (2), 142.

34. McGuire, J.H., 1962, Fire Research Special Report No. 2, HMSO London.

35. Stannard, J.H., 1977, Fire Technology, 13, 35.

36. Lang, R.Z.J., Moorhouse, J., and Paul, G.J., 1980, Institution of Chemical Engineers, Symposium Series No. 58, 275.

37. Eichler, T., et al., 1980, "Study of LNG Spill Dispersion, and Combustion Phenomenology". IIT. Research Institute, Chicago, Report No. J6481.

38. Welker, J.R.,1965, "The Effect of Wind on Uncontrolled Buoyant Diffusion Flames from Burning Liquid". Ph.D. Thesis, Dept of Chemical Engineering, University of Oklahoma.

39. Gollahalli, S.R. and Sullivan, H.F., 1974,"Effect of Pool Shape on Burning Rate, Radiation and Flame Height of Liquid Pool Fires." Report of Thermal Engineering, Group, Dept. of Mechanical Engineering, University of Waterloo, Ontario, Canada.

40. Rospa/ICI, 1970, Liquefied Flammable Gases, Storage and Handling, 15/74.

41. Simms, D.L., and Law, M., 1967, Comb. and Flame, 11, 377.

42. Stoll, A.M., and Greene, L.C., 1959, U.S. Applied Physiology, 14, 373.

43. Seaman, R.E., 1967, Bull N.Y. Acad. Med., 43, 648.

44. Hardee, H.C., and Lee, D.O., 1971, Sandia Laboratories Report, SC-DC-71-4047.

45. Gayle, J.B., and Bransford, J.W., 1965, "Size and Duration of Fireballs from Propellant Explosions", NASA TMX-53314.

46. Van Nice, L.J., and Carpenter, H.J., 1965, "Thermal Radiation from Saturn Fireballs" NAS 9-4810, TRW Systems.

47. High, R.W., 1968, Annals N.Y. Acad. Sci., 152, 441.

48. Hardee H.C., Lee, D.O., and Benedick, W.B., 1977, Comb. Sci. Tech., 17, 189.

49. Fay, J.A., and Lewis, D.H., 1977, "Unsteady Burning of Unconfined Fuel Vapour Clouds", Sixteenth Symposium on Combustion, The Combustion Institute.

50. Hasegawa, K., and Sato, K., 1978, Tech. Mem. Fire Res. Inst. 12, Tokyo.

51. Rasbash, D.J., 1979/80, Fire Safety Journal, 2, 223.

52. Hagglund, B., and Persson, L., 1976,"The Heat Radiated From Petroleum Fires", Forsvarats Forskningsanstalt, Stockholm, FOA Report C20126 - D6.

53. Brotz, W., 1977, Proceedings of the 2nd International Symposium on Loss Prevention, Heidelburg, 297.

54. Hardee, H.C., and Lee, D.O., 1973, Transportation Planning and Technology, 2, 121.

55. Hottel, H.C., and Sarofim, A., 1967, "Radiative Transfer". McGraw Hill

56. Fay, J.A., Desgroseilliers, G.J., and Lewis, D.H., 1979, Comb. Sci. Tech., 20, 141.

57. Gillette, R.H., 1980, Comb. Sci. Tech., 22, 185.

58. Hardee, H.C., and Lee, D.O., 1975, Accid. Anal. and Prev., 7,91.

59. Bader, B.E., Donaldson, A.B., and Hardee, H.C., 1971, J. Spacecraft and Rockets, 12, 1216.

60. Baker, W.E., Cox, P.A., et al, 1978, "A Short Course on Explosion Hazards Evaluation", South Western Research Institute, San Antonio.

61. Hudson, R.D., 1969, "Infra red System Engineering", Wiley, New York.

62. Kruse, P.W., et al, 1962, "Elements of Infra Red Technology - Generation, Transmission and Detection", Wiley.

63. Kondratyev, K.Y., 1965, "Radiative Heat Exchange in the Atmosphere", Pergamon Press.

64. Ludwig, C.B., et al, 1968, "Study on Exhaust Plume Radiation Prediction", NASA, CR-61222.

65. Wyatt, P.J., Stull, U.R., and Plass, G.N., 1962, 1963, "Infra Red Transmission Studies Final Report", Volume II (Water Vapour), Volume III (Carbon Dioxide), SSD-TDR-62-127.

66. NTSB, 1972, "Derailment of Toledo, Poerin and Western Railroad Company's Train No. 20 with Resultant Fire and Tank Car Rupture, Crescent City, Illinois, June 21 1970", National Transportation Safety Board Report, NTSB-RAR-72-2.

67. NTSB, 1973, "Propane Tractor-Semitrailer Overturn and Fire, Lynchburg", NTSB-HAR-73-3.

68. Anonymous, 1974, Fire Journal, 52.

69. Lathrop, J.K., 1974, Fire Command, 14.

70. Anonymous, 1974, Fire Prevention, 106, 38.

71. NTSB, 1978, Railroad Accident Report. Belt, Montana, NTSB-RAR-77-7.

72. NTSB, 1978, "Collision of a Louisiana and Arkansas Railway Freight Train and a LV Rhymes Tractor-Semitrailer at Goldanna, Louisiana, December 28, 1977", NTSB-RHR-78-1.

73. NTSB, 1978, Railroad Accident Report, Lewisville, Arkansas, NTSB-RAR-77-1.

74. Hayes, T.C., 1972, Fire Command, 12.

75. Glasstone, S., 1962, The Effects of Nuclear Weapons, United States Atomic Energy Commission.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions made by colleagues within British Gas in the preparation of this paper, and in particular Mr. P. Cronin, Mr.K.G. Kinsella and Mrs.C. Pearson.

This paper is published by permission of British Gas.

Table 2: Data on Incidents Resulting in Fireballs

Incident No.	Ref.	Date	Place (All USA Unless stated)	Fuel Container	Fuel	Quantity Involved (tonnes)	Reported Fireball Diameter (m)	Comments
1	(66)	21.06.70	Crescent City, Illinois	Rail Tank Car	Propane	75	150 - 200	Fireball rose 250m
2	(67)	09.03.72	Lynchburg, Virginia	Tank Truck	Propane	9	120	
3	(68)	05.07.73	Kingman, Virginia	Tank Car	Propane	45	300*	* After fireball lifted off from ground. Prior to lift off diameter was 90-120m
4	(69)	11.01.74	West St. Paul, Minnesota	Tank	LPG	10	100	Fireball rose about 100m
5	(70)	17.01.74	Aberdeen, Scotland.	Road Tanker	Butane	2	70	Actual dimensions were 140 x 60 x 20m
6	(71)	26.11.76	Belt, Montana	Rail Tank Car	LPG	80	300	
7	(72)	28.12.77	Goldanna, Indiana	Rail Tank Car	LPG	70	300 - 350	Fireball rose about 300m
8	(73)	29.03.78	Lewisville, Arkansas	Rail Tank Car	Vinyl Chloride	110	305	
9	(74)	19.10.71	Houston, Texas	Rail Road Car	Vinyl Chloride	165	300	

Table 3: Summary of Fireball Data (* Based on maximum diameter) (‡Based on total fuel mass plus oxidant)

Researcher	Fuel	Method of Containment and Ignition	Fuel Mass Range (kg)	Maximum Fireball Diameter (m)	Fireball Duration (seconds)	Height of Fireball Centre above Ignition point (m)	Effective Emissive Power (kWm^{-2})
Fay and Lewis (49)	Methane Ethane Propane	Quiescent samples contained in soap bubbles and ignited by a hot wire	$4x10^{-5}$ - $4x10^{4}$	$6.36W^{0.333}$	t_b, $2.57W^{0.167}$	$10.3W^{0.333}$	32 21 52
Hardee et al (48)	Methane (Pure methane and and stoichiometric methane)	- Quiescent samples contained in polythene bags and ignited by a hot wire	Theoretical 0.1 - 10	$6.24W^{0.33}$	t_L, $1.11W^{0.167}$	- -	123
Hasegawa and Sato (17)	Pentane	Pressurised release. Fuel in glass spheres which were heated internally prior to rupture of vessel with vapour being ignited by a pilot flame	0.3 - 6.2	$5.28W^{0.277}$	t_d, $1.099W^{0.097}$		110 - 128
Hasegawa and Sato (50)	Pentane Propane Octane	As above with fuel samples held in a steel tank	0.3 - 31	$5.25W^{0.314}$	t_d, $1.07W^{0.181}$	1-1.5D *	152 - 250
Gayle and Bransford (45)	Rocket fuels (Kerosene/Liquid oxygen and liquid hydrogen)	Pressurised releases from tanks with immediate or delayed ignition by an external source	$1 - 10^{5}$	$6.14W^{0.325}$	t_{tot}, $0.41W^{0.349}$		Adiabatic flame temperature
Van Nice and Carpenter (46)	Rocket Fuels	As above	10^{5} - 10^{6}	-	-	~3D*	
High (47)	Rocket Fuels	As above	$1 - 5 \times 10^{3}$	‡ $3.86W^{0.32}$	‡ $0.3W^{0.32}$	~0.7D	

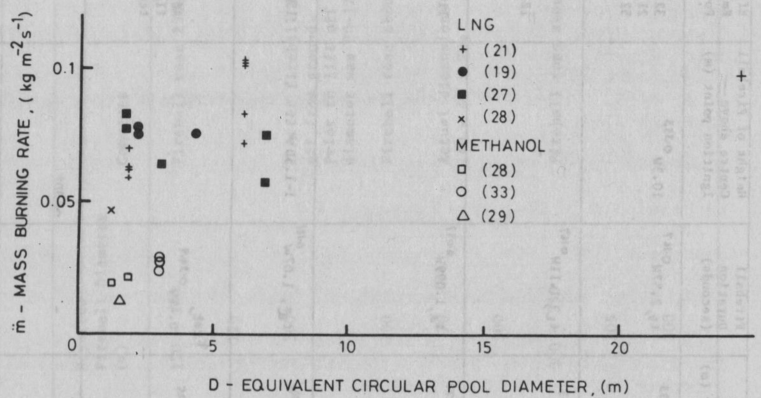

Figure 1 Mass burning rate data for methanol and LNG

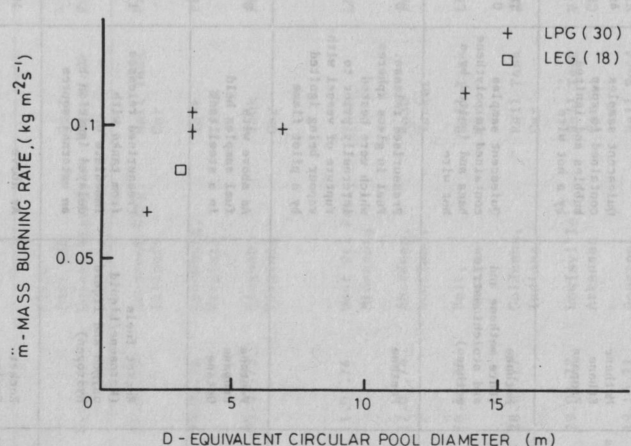

Figure 2 Mass burning rate data for LPG and LEG

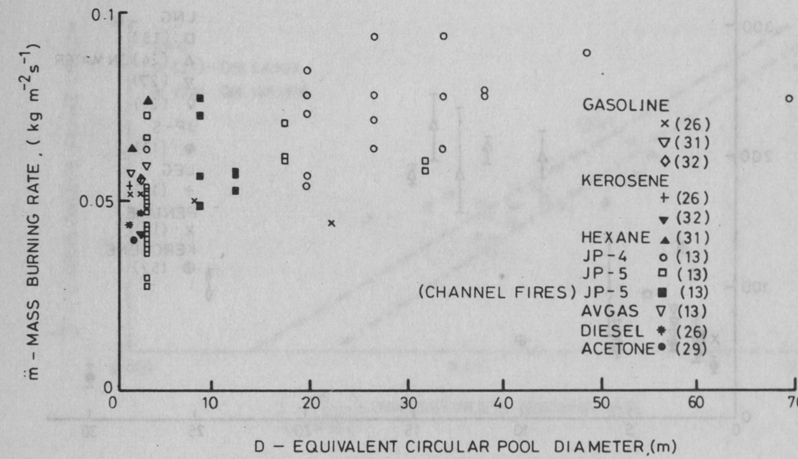

Figure 3 Mass burning rate data for liquid hydrocarbon fuels

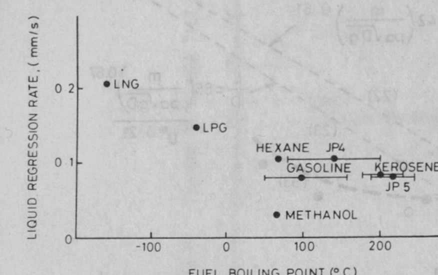

Figure 4 Influence of fuel boiling point on liquid regression rate

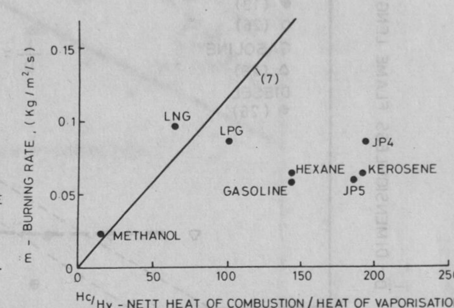

Figure 5 Influence of Hc/Hv on mass burning rate

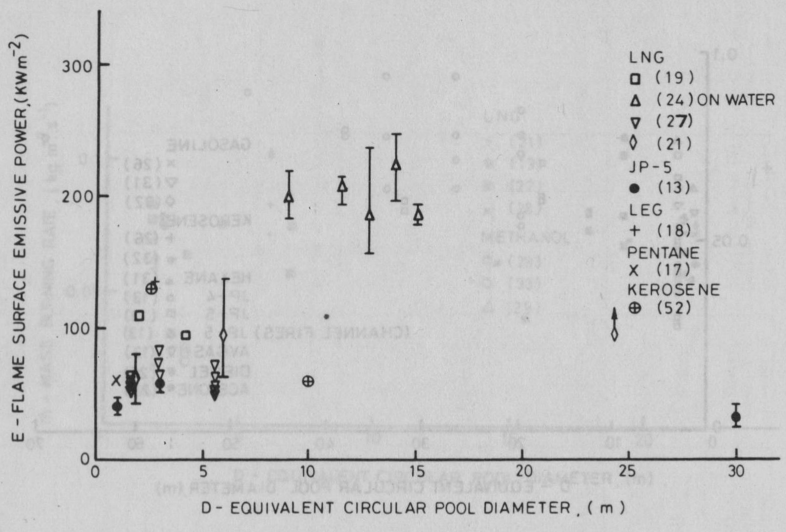

Figure 6 Dependence of flame surface emissive power on equivalent circular pool diameter

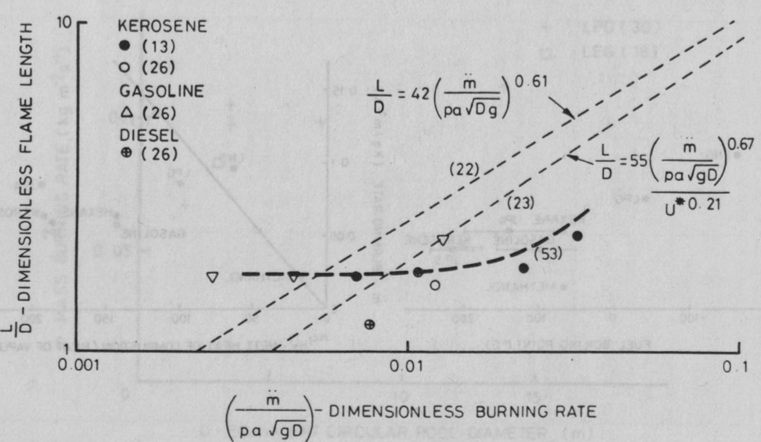

Figure 7 Influence of dimensionless fuel burning rate on flame length for hydrocarbon pool fires

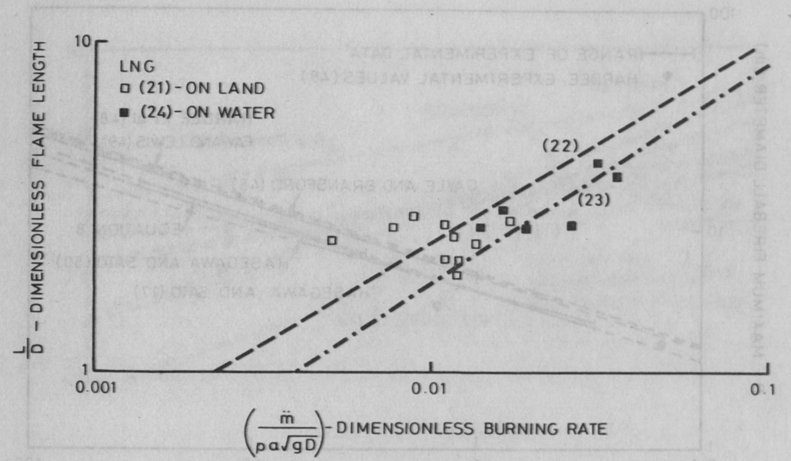

Figure 8 Influence of dimensionless fuel burning rate on flame length for LNG pool fires

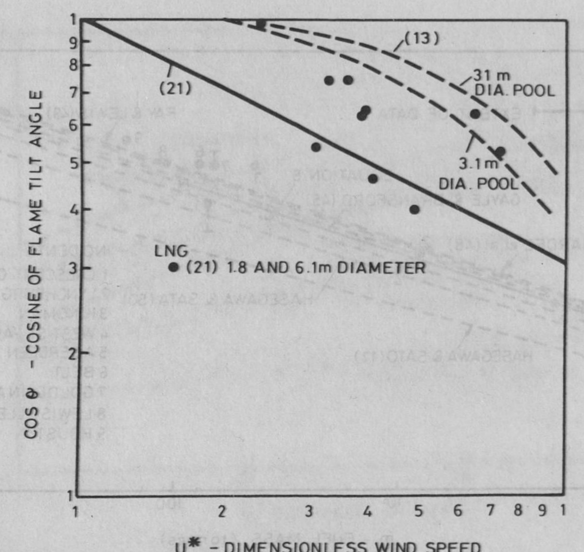

Figure 9 Dependence of flame tilt angle on dimensionless wind speed

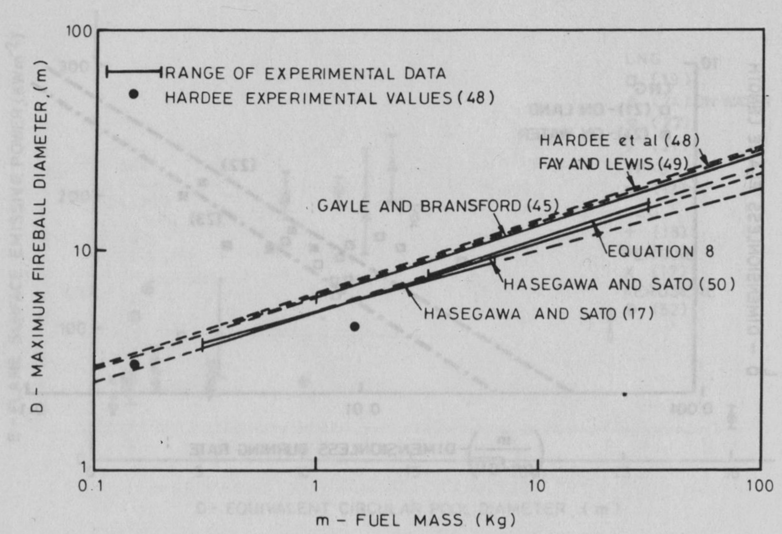

Figure 10 Influence of mass of fuel released on the maximum fireball diameter

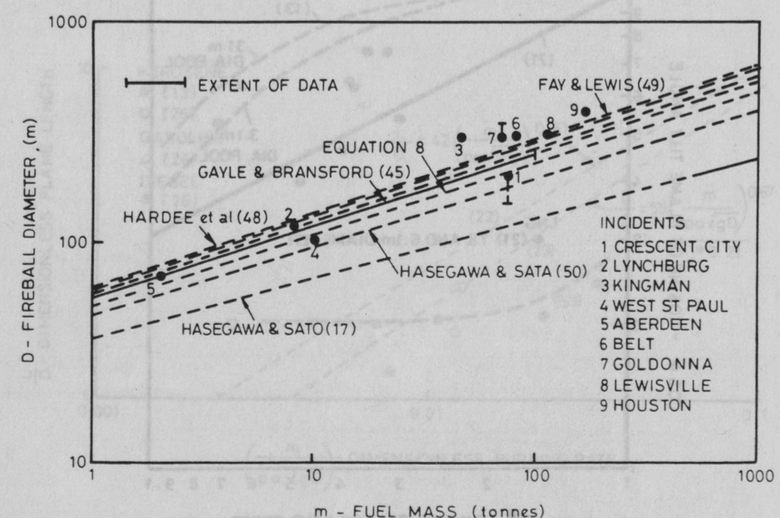

Figure 11 Influence of mass of fuel released on the maximum fireball diameter

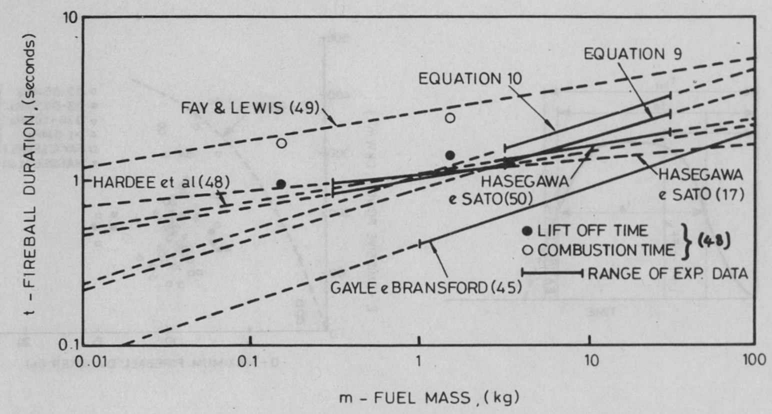

Figure 13 Dependence of fireball duration on fuel mass released

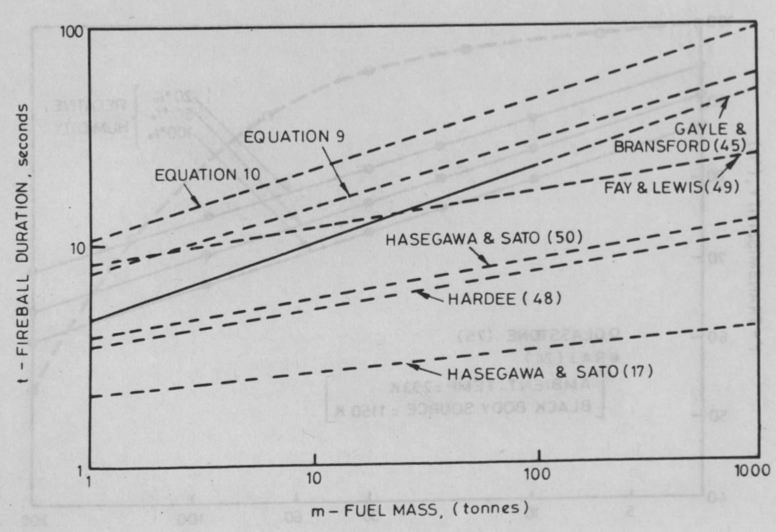

Figure 14 Dependence of fireball duration on fuel mass released

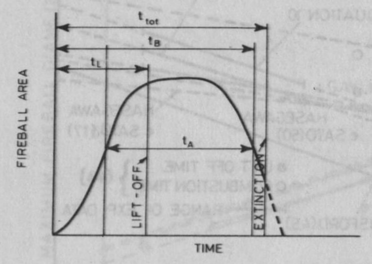

Figure 12 Representation of various fireball time parameters

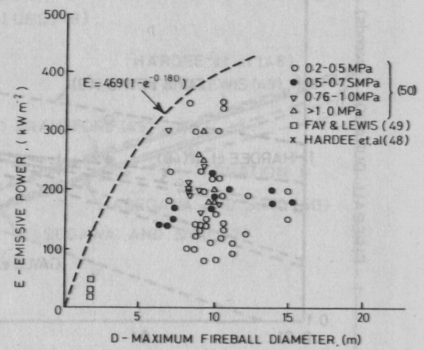

Figure 15 Influence of maximum fire-ball dia. on surface emissive power

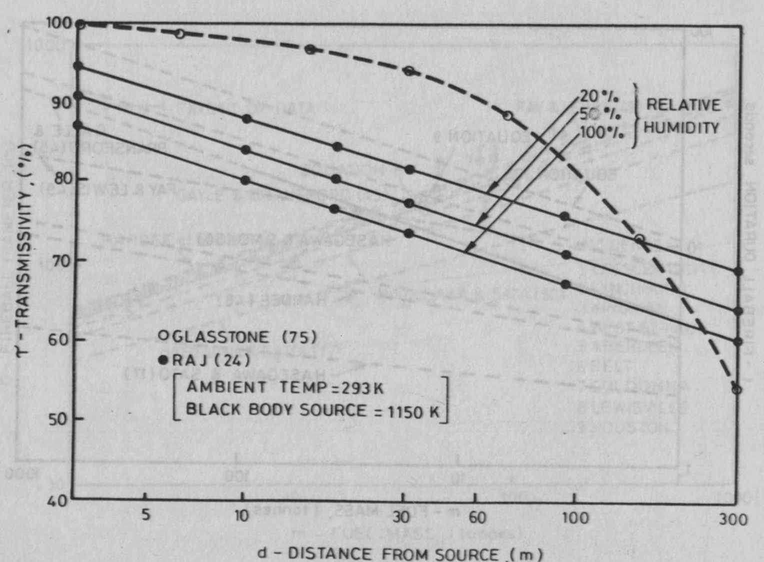

Figure 16 Transmission of infra red radiation through the atmosphere