FACTORS CONTROLLING BURNING TIME FOR NON-PREMIXED CLOUDS OF FUEL GAS

H.C. Jaggers, D.P. Franklin, D.R. Ward, F.G Roper*

Dimensional analysis is used to systematise the available data on fireball burning times from pressurised and non-pressurised fuel releases. It is shown that, for fully turbulent fireballs, the burning time is proportional to the one sixth or one third power of the fuel mass for the limiting cases of buoyancy control or release velocity control respectively. As the maximum release velocity is in the region of sonic, this analysis implies constraints on the possible burning times for large fuel releases.

New data are presented covering a fuel mass range of six orders of magnitude (0.012g to 11.9kg): more than five hundred soap bubble and balloon experiments were performed. It is shown that small spherical soap bubbles of less than 0.5g fuel do not produce fully turbulent fireballs and cannot be used to make predictions about large fireballs. However, the large spherical soap bubble data (0.5 to 14g) are probably unique in representing quiescent release conditions, protected from wind influence, yet large enough to give fully turbulent buoyancy-controlled fireballs.

Some preliminary work is reported on flames from disc-shaped propane bubbles, representing a pancake cloud of dense fuel gas on the ground. The observed behaviour was quite different from that reported by earlier workers.

Keywords: Fireballs, Burning time, Velocity control, Buoyancy Control.

INTRODUCTION

One aspect of hazard assessment requiring further study is the combustion behaviour of a large fuel gas cloud that is ignited before significant mixing with air. In some circumstances, such as a high-pressure release or BLEVE, the fuel gas may lift off the ground while still burning. We need to know under what conditions such behaviour could result, and if a fireball is formed, how to predict the parameters that govern the heat radiated.

*British Gas Corporation, London Research Station, Michael Road, London SW6 2AD.

The main factors that control the heat radiated from a burning cloud of fuel gas are: fireball diameter and rise height, burning time, and surface emissive power. Most workers are in agreement that the fireball diameter and rise height may be scaled as the fuel mass to the power of one third (Fay and Lewis, 1976; Moorhouse and Pritchard, 1982; Roberts, 1981/2). Likewise, much useful data on surface emissive power may be obtained from pool fires of LNG and LPG (Moorhouse and Pritchard, 1982; Mizner and Eyre, 1983; Mudan, 1984), and the fireball experiments of Hasegawa and Sato (1978). These experiments give emissive powers less than a quarter of that predicted from the adiabatic flame temperatures assumed for fireballs by some early workers.

In contrast there is no such agreement as to the relationship between burning time and fuel mass. Various workers have found that burning time is proportional to (fuel mass)^n where n varies in the range 0.1 to 0.35 (Moorhouse and Pritchard, 1982). These relationships, if extrapolated to large masses of fuel gas, would give considerable variation in predicted burning times. This paper shows that the available data on burning time may be systematised using dimensional analysis, and reports new data covering a mass range of six orders of magnitude.

THEORY

In the past, various workers have given theoretical models for a fireball that make detailed assumptions about the mechanisms involved. However, our present state of knowledge seems unable to support such a development. For instance, a momentum balance on the fireball motion shows that only a small part of the entrained air is mixed and burnt with the fuel. No accurate data are available on the proportion of the unburnt air, although it has a large effect on the motion and lifetime of the fireball.

In this situation one can obtain much information from dimensional analysis. Although this method gives no detailed information, it provides scaling laws of general validity that are very powerful when combined with appropriate experimental data. For instance, Fay and Lewis (1976) have considered the case of a fireball controlled by buoyancy forces, finding a 1/6 power law between burning time and fuel mass. Roberts (1981) has pointed out that in contrast a momentum controlled release would give a 1/3 power law. It is useful to extend this analysis to the general case where both buoyancy and initial momentum must be considered.

For the case of a high velocity release there is much uncertainty as to what happens during the short period of the release. For instance, the behaviour of the initial jet will depend on the fracture mode of the container. If the fuel is initially in the form of a superheated liquid, a complete description of the release involves complex problems of two-phase flow. It is useful to take an analogy with turbulent jet diffusion flames, where the detailed behaviour close to the nozzle is often uncertain. For such diffusion flames, it is found that profiles of concentration, velocity, and temperature quickly reach a self-similar state. The flame behaviour is then controlled by integral properties such as fuel mass flowrate, momentum flux, and ratio of buoyancy generated momentum to initial momentum. In the case of a jet release of short duration, the fuel initially released forms a starting vortex moving with reduced velocity, so that fuel in the jet behind it can catch up and also be entrained. This suggests that the fireball will also reach a self-similar state, with the initial details of release being quickly forgotten. In other words, the fireball behaviour should be controlled by integral quantities such as mass released, initial momentum, and buoyancy generated momentum. If the initial momentum is calculated from the release conditions or measured from the reaction on the container, a mean release velocity v_o can be defined as:

$$v_o = \frac{\text{Initial momentum of release}}{\text{Mass of fuel released}}$$

On the assumption of geometric similarity , the fireball behaviour may be described in terms of the following dimensionless groups. The symbols are given in the nomenclature.

$t_* = t_B g^{\frac{1}{2}} \ (\rho_o/M_f)^{1/6}$	Dimensionless time
$v_* = (v_o/g^{\frac{1}{2}}) \ (\rho_o/M_f)^{1/6}$	Dimensionless velocity or Froude number.
(ρ_o/ρ_f)	Density ratio
(Mass of air/mass of fuel) for complete combustion	*Stoichiometric mass ratio*
(T_b/T_o)	Temperature ratio
$R(\rho_o/M_f)^{1/3}$	Dimensionless radius
$h(\rho_o/M_f)^{1/3}$	Dimensionless rise height
$\frac{M_f \ g}{\rho_o \ \nu^2} \ \left(\frac{T_b - T_o}{T_o}\right)$	Grashof number
$(\nu\rho C_p \ /\lambda)$	Prandtl number
(ν/D)	Schmidt number
$(g/C_pT_o) \ \ (M_f/\rho_o)^{1/3}$	Temperature rise due to dissipation of gravitational energy

In deriving the above groups, the characteristic length was taken as $(M_f/\rho_o)^{1/3}$, which is proportional to fireball diameter for a given temperature ratio.

Most of these dimensionless groups may be neglected when scaling fireball behaviour. The last term in the above table represents the temperature rise due to conversion of gravitational energy to heat, and is negligible. The Prandtl and Schmidt numbers for common gases are almost constant and close to unity. For hydrocarbon gases, the temperature ratio and stoichiometric mass ratio are almost constant, and so may be neglected. The dimensionless radius and rise height for the fireball are found experimentally to be almost constant, and so may be neglected when scaling other characteristics.

The Grashof ratio (Gr) is proportional to the square of a Reynolds number (Re) based on the buoyant rise velocity and fireball diameter. It is a measure of viscous effects on the fireball. In fluid flow it is commonly *found that, so long as Re is large enough to ensure fully developed* turbulence, the properties of the flow are independent of Re. In other words, variations in Gr may be neglected so long as Gr is large enough to ensure fully turbulent flow.

The remaining groups are the dimensionless time and velocity, and the density ratio. The evidence so far suggests that variations in fuel gas density are unimportant so long as the results are expressed in terms of the groups shown above. However, future experimental results should be checked for any effect of fuel gas density.

This implies that the dimensionless time and velocity are related, i.e.

$$t_B g^{\frac{1}{2}} \left(\frac{\rho_o}{M_f}\right)^{1/6} = f\left\{\frac{v_o}{g^{\frac{1}{2}}} \left(\frac{\rho_o}{M_f}\right)^{1/6}\right\}$$

There are two limiting cases: (i) Release velocity negligible. In this case, the dimensionless time is constant, i.e.

$$t_B \alpha \left(\frac{M_f}{\rho_o}\right)^{1/6} g^{-\frac{1}{2}}$$

(ii) Release velocity large, and buoyancy negligible. In this case the *results must be independent of* g, *i.e.*

$$t_B\, g^{\frac{1}{2}} \left(\frac{\rho_o}{M_f}\right)^{1/6} \alpha \frac{g^{\frac{1}{2}}}{v_o} \left(\frac{M_f}{\rho_o}\right)^{1/6}$$

i.e.

$$t_B \alpha \frac{1}{v_o}\left(\frac{M_f}{\rho_o}\right)^{1/3}$$

In the transition region, t_B must be less than the buoyancy controlled limit, as any initial momentum will increase mixing rates of fuel and air.

This discussion may be generalised to state that a 1/3 power law between burning time and fuel mass implies control by a characteristic velocity of the system. This may be the initial release velocity as discussed above. However, control by any other velocity, for instance the burning velocity of the fuel gas, would give a similar relationship.

This analysis can explain the variety of relationships found for burning time versus fuel mass. The equations given above predict the following features on a graph of t_B versus M_f.

(i) A buoyancy controlled line, $t_B \alpha M_f^{1/6}$, representing the maximum possible value of t_B.

(ii) A family of velocity controlled lines, $t_B \alpha M_f^{1/3}$, rising to meet *the buoyancy controlled line. Each separate line represents a* different value of the release velocity.

For a given release velocity, as the fuel mass increases, the effects of buoyancy will increase and eventually become dominant. Thus as the fuel mass increases, the burning time will become proportional to the fuel mass to the power of 1/6 rather than 1/3. The mass for which this transition occurs will depend on the release velocity.

EXPERIMENTAL METHOD

The experiments involved ignition of a measured volume of fuel-gas under controlled conditions. A video or cine film record was made of the resulting fireball, and this was analysed to give fireball diameter, rise height, and burning time. Checks were made for image persistence on the video camera, to avoid overestimating the burning time. In some cases the records were supplemented by high-speed schlieren photography. The phases of the work reported here were as follows:

i) Methane and propane fuel gas contained in small spherical soap bubbles in a laboratory, with mass ranging from 0.013 to 0.35g (20 to 200 cm^3). The bubbles were blown on a 20 mm diameter upwards-facing pedestal well clear of the ground. They were burst and ignited by an electrically heated wire. Excess pressures within the bubbles were of the order of a few Pa.

ii) Fuel gas contained in spherical soap bubbles in a pilot plant laboratory. These tests allowed fireballs up to 1.6m diameter to be investigated, with quiescent release in wind-free conditions. The mass range was from 0.012 to 14g ($10cm^3$ to $12dm^3$), i.e. 3 orders of magnitude. The fuel gas used in most of the experiments was a neutrally buoyant mixture of 90% ethane and 10% methane. For other fuel gases, the maximum bubble size was limited by buoyancy forces. Some experiments were carried out on methane up to the limit possible on our apparatus (1.5 dm^3 or 1 g). Ignition was by a small spark-ignited pilot flame.

For the largest bubbles used in these tests, the time for the flame to travel across the sphere of fuel gas became significant, about 10% of t_B. (The flame travel time varied approximately as the bubble diameter). As fireball development depended on the buoyant rise of the flame gases, the burning time was taken to start when 50% of the fuel gas was ignited.

A schematic diagram of the apparatus is given in figure 1. The bubble pedestal was supported by a light framework about 2m above ground. The pedestal had a diameter of 20 or 55 mm, depending on the fuel volume, and was packed internally to reduce the dead volume. For the larger bubbles, it was necessary to use a downwards pointing pedestal, with the bubble hanging below it. This caused the fireball to pass over the supporting rod, giving some visible disturbance. A comparative set of tests was carried out with small bubbles (for which the effect of such disturbance should be most severe), with the bubble first above then below the support. Little effect was found of bubble orientation on burning time.

A viscous soap solution was developed to allow these large bubbles to be blown. The composition was 250 cm^3 of 2.5% (w/w) sodium oleate in distilled water, 135 cm^3 glycerol, and 200g of sucrose. The surface tension was 0.027 N/m, giving excess pressures less than a few Pa.

These tests were performed under remote control, with provision for dispersing the fuel gas safely should a bubble burst prematurely.

iii) Methane and propane fuel gas contained in toy balloons out of doors. The mass range was from 0.2g to 0.46 kg (300 cm^3 to 250 dm^3). Ignition was by a small petrol flame, which was itself lit by a hot wire. A vigorous ignition source was needed to avoid blow-out.

The internal excess pressure for similar balloons was later found to be in the range 3 to 5 kPa. It was not measured at the time, because (in common with many other workers) we did not realise that such low pressures were significant. The excess pressure varied only slightly with balloon volume: although the skin tension increased with radius, the pressure was proportional to skin tension divided by radius. Three additional experiments were also carried out with from 6.1 to 11.9 kg of methane contained in meteorological balloons.

iv) Disc-shaped propane bubbles in a laboratory, representing on a very small scale a flattened cloud of dense gas lying on the ground. Disc diameters were from 100 to 200 mm, with thickness from 5 to 34 mm. Fuel masses ranged from 0.07 to 2g. Ignition was by an electrically heated wire.

The disc bubbles were blown with the aid of a thin metal ring, supported at the appropriate distance from a large horizontal surface by metal rods. A sheet of perspex was placed on top of the ring, with all the surfaces wetted by soap solution. A bubble of fuel gas was blown under the perspex sheet, which was then slid off to leave a disc bubble on the metal frame-work.

At least 6 replicate tests were usually carried out for each set of conditions in phases (i) to (iv). The data reported here represent the following numbers of tests: 120 in phase (i), 190 in phase (ii), 115 in phase (iii), and 89 in phase (iv).

RESULTS AND DISCUSSION

Spherical Fireballs clear of the Ground

When considering scaling laws, an important question is the fuel mass above which the fireball enters the high Reynolds number regime, where viscous effects are neglible. The results of our film and video observations showed very clearly that bubble fireballs with less than about 0.5g of fuel were not in this regime. In contrast, fireballs from larger bubbles corresponded fairly closely to observations of large releases, such as BLEVEs. Fireballs formed from more than 0.5g of fuel gas approximated to a flattened sphere (before they broke up), and were highly turbulent. They formed a ring vortex, as predicted by classical hydrodynamics for a bubble of one fluid moving through another. This vortex form could be seen very clearly from above during the second half of the fireball lifetime (plate 1 (a)). The ring vortex could also be seen in cross section during the break-up phase (plate 1(b)). Sometimes the axis of the vortex ring tilted from the vertical, so that the ring could be seen from the side.

For very small bubbles (ca. 20 mg of fuel gas), the fireball was more filamentary in form, with much variation presumably due to small variations in release conditions. Typically, the very small fireballs were elongated vertically, with a small mushroom at the top. Although their structure was disordered, it was not fully turbulent. Slightly larger fireballs started in this vertically elongated form, and then developed into the spherical vortex form of the large fireballs. This behaviour can be seen in the photographic sequence shown by Fay and Lewis (1976). As the fuel mass became larger, the relative duration of the elongated phase decreased, until it disappeared. These variations in form are shown in plates 1(c) to 1(e).

These changes in fireball appearance were matched by similar changes in other properties such as burning time. The burning times for our bubble fireballs (phases (i) and (ii)) are shown in detail in figure 2. For fuel masses greater than 0.5g, the burning time followed a 1/6 power law against fuel mass (line A), as predicted for buoyancy control. But smaller bubbles followed a different relationship, close to a 1/3 power law (line B). The reason for the change presumably is that the small bubbles are not in the high Reynolds (or Grashof) number regime. The Reynolds number for fireballs in the transition region, based on visible diameter and evaluating the viscosity at a mean temperature between fireball and ambient conditions of 1100K, was about 2000.

This change in slope may be seen most clearly for the phase (ii) experiments with fuel gas 90% ethane + 10% methane, which provide a consistent set of data over a mass range of 10^3. A single power law for t_B versus M_f could not be fitted over the complete mass range. For $M_f \geqslant 0.6$g, the exponent of M_f was found to be 0.178 ± 0.007, which does not differ significantly from the theoretical value of 1/6 for buoyancy control. For $M_f \leqslant 0.12$g, the exponent of M_f was found to be 0.324 ± 0.044. Analysis of the phase (i) results also yielded a slope close to 1/3 for fuel masses less than 0.5g.

The practical implication of these results is the difficulty of making deductions about large fireball behaviour from experiments on less than about 0.5g of fuel.

The results for 1g or less of fuel, for which it was possible to use a range of fuel gases, showed little effect of gas composition on burning time. For very small fuel masses, there was some difference between the first (CH_4, C_3H_8) and second (CH_4, C_2H_6-CH_4 mixture) set of experiments. This was probably due to a difference in experimental technique. The hot wire ignition used in our first experiments gave a slight delay between bubble bursting and ignition, with some premixing of fuel and air. The effect could be seen in the blue rather than yellow colour for the smallest CH_4 fireballs in our first set of experiments.

A summary of the available data on fireball burning times is shown in figure 3. Line A again represents our measurements on bubble fireballs for fuel masses greater than 0.5g. We think that these results are probably unique in representing a quiescent release, protected from wind and yet large enough to be fully turbulent. The theoretical extrapolation of this line lies somewhat above all the other data, as would be expected for a fully buoyancy controlled release. For practical incidents, fireball burning times should be below this line, as disturbances due to wind or release effects are inevitable.

The results of Fay and Lewis lie close to our small bubble measurements, although we find a different slope in this region. It is difficult to be precise about the correct slope for their results, due to their small mass range (x20) combined with the inherent random variation in fireball burning times. A small change in any systematic errors could also affect the apparent slope over a small range. Our own results covered a mass range of 10^3 for soap bubbles, and included duplicate sets of measurements with different apparatus and personnel.

In order to extend the mass range of the experiments, we used fuel gas contained in toy balloons up to 0.46 kg. The results were quite different from the soap bubble experiments, despite overlapping in mass range, and are shown by the line C in figure 3. The slope of this line is approximately 1/3, corresponding to control by the velocity of release. We have no direct data on this velocity, as its significance was not initially realised. However, the internal pressure (measured subsequently) was 3 to 5 kPa, which would imply a release velocity of several tens of metres per second.

Other data plotted in figure 3 include the results of Baker (1979) (line D) and Hasegawa and Sato (1977, 1978) (line E) for pressurised releases of propane and other hydrocarbons. For Baker's results, the degree of superheat was probably sufficient to ensure a single-phase discharge close to sonic velocity. The effect of this release velocity in reducing the burning time can easily be seen. For instance, the time is a factor of 4 smaller than for meteorological balloon releases with similar masses of fuel. The burning time for Baker's 10kg of high pressure propane is also a factor of two smaller than for Hardee et al's (1978) balloon/polythene bag releases with 1.5kg of fuel, or our own bubble fireballs with 0.015kg of fuel. On the present theory, such pressurised releases would change from velocity to buoyancy control at a fuel mass somewhere in the region of 50 tonnes.

The measurements of Hasegawa and Sato were probably also velocity controlled. However, the degree of superheat was usually not sufficient to give a single-phase release, so that it is difficult to estimate the release velocity.

An important question which next arises is: Can we relate the various velocity controlled lines in Figure 3? From the theory in section 2, under velocity control the burning time should be inversely proportional to release velocity, for a given fuel mass. At present we have no hard data on release velocities. However, the velocity for a high pressure release through a sharp-edged orifice should be close to sonic, approximately 250 m/sec for propane. If the lines C and D are related in this way, this would imply a release velocity of about 60 m/sec for our balloon experiments, close to the theoretical value for a continuous release of propane from an internal pressure of 4 kPa. We are now starting to measure our release velocities, from the reaction on the container, to clarify this point.

The NASA relationship of Gayle and Bransford (1965), adjusting their data for fuel plus oxidant to mass of fuel alone, is also shown on figure 3 as line F. This also has a slope close to 1/3, corresponding to velocity control. It is difficult to know to what extent the burning time was affected by the simultaneous release and possible premixing of oxidant and fuel.

The above considerations place constraints on the possible relationships between burning time and fuel mass. The maximum possible burning time corresponds to buoyancy control:- lines A and B in figure 3. The highest possible release velocity for a sharp-edged orifice will be in the region of sonic, presumably corresponding to lines D or F. Thus the possible range of burning times will lie in the area between the lines A, B, and D or F. For fuel masses greater than those in this area, the burning time should lie along the extension of line A. However, for large fuel masses, the time for release must also be significant, and may even exceed the burning time. In this case, premixing with air during the release phase would tend to reduce the burning time.

Fireballs from Disc-shaped Bubbles on the Ground

We performed some preliminary experiments using a dense fuel gas (C_3H_8) in disc-shaped bubbles on the ground, for comparison with the work of Lewis

(1977). Fuel volumes ranged up to 1 dm^3, with aspect ratios from 6 to 50.

Two stages could be identified in the combustion process. Soon after ignition, there was a puff of flame which rose from the ground and burnt as a roughly coherent expanding volume. This we identified with the fireball of Lewis (1977), as its duration was similar. As this initial puff faded, further burning occurred from the ground as random, overlapping, tongues of flame which continued with diminishing intensity until all the fuel had been consumed. This stage looked like a small pool fire.

Although there were clearly two stages of combustion - an initial transient and a pseudo-steady state - the dividing line was a subjective one. It is probably more accurate to describe the initial fireball as the starting plume (Turner, 1962) for the following buoyant diffusion flame or 'pool fire'. The rate of supply of fuel gas to both stages was governed by the rate at which the dense fuel could be heated and caused to rise, presumably by convective heat transfer.

This second 'pool' fire stage was not mentioned by Lewis (1977) or Fay and Lewis (1976), although it clearly represented the burning of a major proportion of the available fuel. Figure 4 shows the variation of flame height with time for a typical case. The flame height in the 'pool fire' stage decreased with time because of the steady reduction in diameter of the cloud of fuel at its base. The duration of the 'initial fireball' is shown on the figure. The scatter is caused mainly by the oscillations in instantaneous flame height. We made some measurements of the diameter, rise height, and burnout time for the 'fireball' stage. The accuracy was unfortunately limited by the subjective element in deciding, for instance, what was the end of the fireball. From these measurements it was possible to make some estimate of the mass of fuel in the initial transient, by working backwards using relationships derived for spherical bubble fireballs. These estimates were reasonably consistent (subject to a fairly large random scatter), and were equivalent to a layer of fuel only a few millimetres thick from the top of the disk. Our estimates of the proportion of fuel entering the initial transient ranged from 5 to 30%. The latter figure was found only for very shallow bubbles.

Much further work would be needed to establish how such small-scale data can be related to releases of practical interest. However, we think that these results are relevant because they disagree with suggestions, based on similar small-scale work (Lewis, 1977; Fay and Lewis, 1976), that the major part of a pancake-shaped cloud of dense fuel gas would lift off the ground and burn as a fireball.

In order to interpret data from scaled-down experiments on the burning of dense fuel gas clouds lying on the ground, there are several questions to be answered. One such question concerns the scaling law for heat transfer downwards from the flame to the dense fuel gas, which will control the entrainment rate of fuel. The times taken to complete various controlling processes must also be considered. For instance the experiments at Maplin Sands (Mizner and Eyre, 1983) have shown that, for a thin cloud, the time taken for a flame to travel across the cloud can exceed the hypothetical fireball burning time. In this case, a fireball could not form, as the fuel would be burnt out before it could gather into a compact shape.

CONCLUSIONS

The observed data on fireball burning times can be correlated in a systematic manner by dimensional analysis. So long as the fireball is large enough to be fully turbulent, this results in a correlation between dimensionless burning time (as defined in this paper) and the Froude number based on release velocity. Under buoyancy controlled conditions, the burning time is found to be proportional to fuel mass to the power of one sixth. When the mixing rate of air into the fireball is controlled by the fuel release velocity, then the burning time is proportional to the fuel mass to the power of one third. The case of buoyancy control will represent the maximum burning time for a given fuel mass, as any initial fuel momentum will increase mixing rates.

Our experimental results using large soap bubbles agree with the one sixth power law originally proposed by Fay and Lewis (1976) for buoyancy control. However, this relationship does not appear to hold for fuel masses less than about 0.5 g (750cm^3 of methane), as the resulting fireballs are not fully turbulent. This implies that it is difficult to make deductions about large fireball behaviour from experiments on less than about 0.5g of fuel.

Preliminary experiments on small disc-shaped bubbles of dense fuel gas show that only a part of the fuel is entrained in an initial 'fireball'. The major part burns more slowly in a 'pool fire' mode.

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NOMENCLATURE

C_p	Specific heat
D	Diffusion coefficient
g	Acceleration due to gravity
h	Fireball rise height
M_f	Fuel mass
R	Fireball radius
t_B	Fireball burning time
t_*	Dimensionless burning time
T_o	Ambient temperature
T_b	Temperature of combustion products
v_o	Initial fuel release velocity
v_*	Froude number or dimensionless velocity

λ Thermal conductivity

ν Kinematic viscosity

ρ_o Density of ambient air

ρ_f Fuel density

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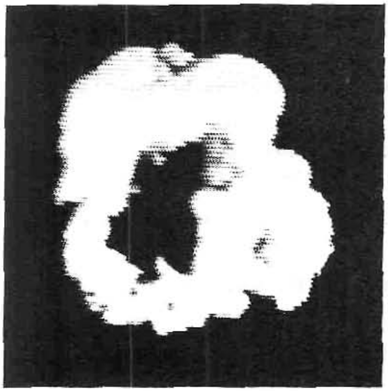
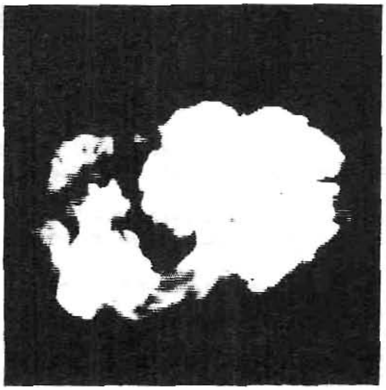
Plate 1. Soap bubble fireballs. Fuel: 90% ethane plus 10% methane.



(a)

Fireball from $3dm^3$ bubble, 3.5g fuel. Viewed from above to show vortex ring structure.



(b)

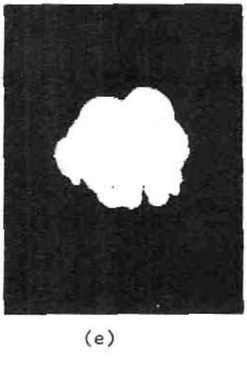
Fireball from 5 dm^3 bubble, 5.8g fuel. Viewed from side during break up phase to show cross section of vortex structure.

(c)

$11.5cm^3$ bubble, 0.013g fuel.

(d)

$100cm^3$ bubble, 0.12g fuel.



(e)

5 dm^3 bubble, 5.8g fuel.

Plates 1(c) to 1(e) show typical changes in fireball structure with increasing fuel mass.

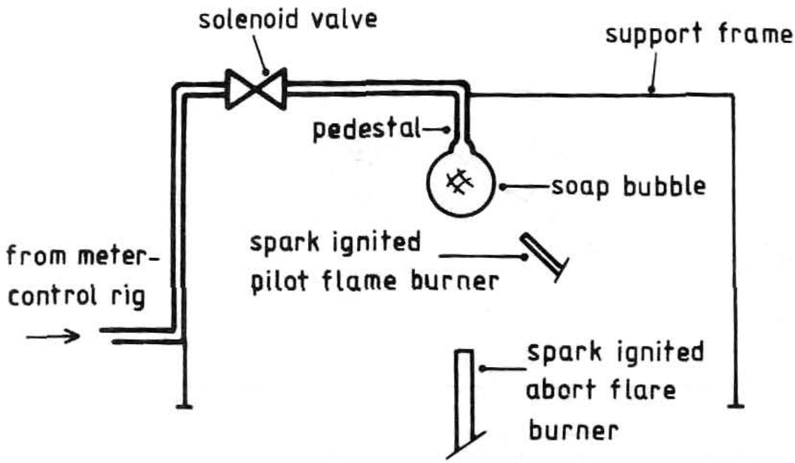


Fig. 1. Schematic diagram of the large bubble apparatus.

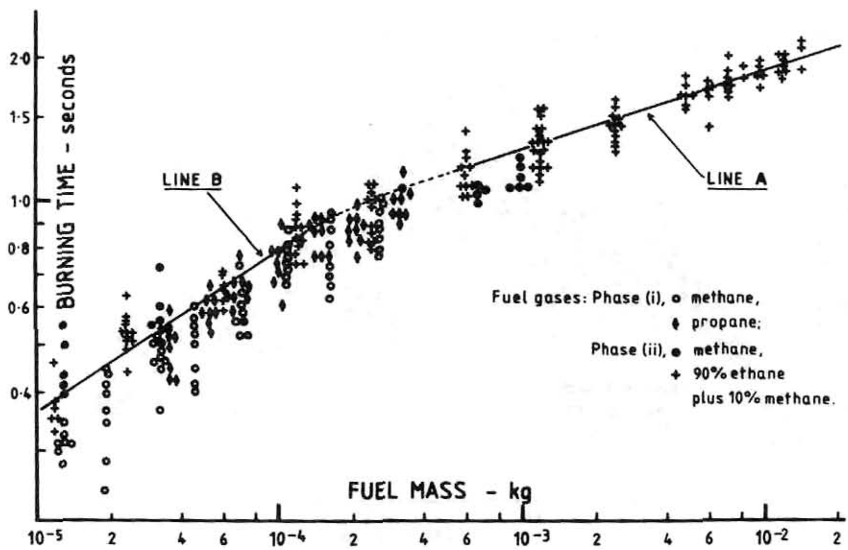
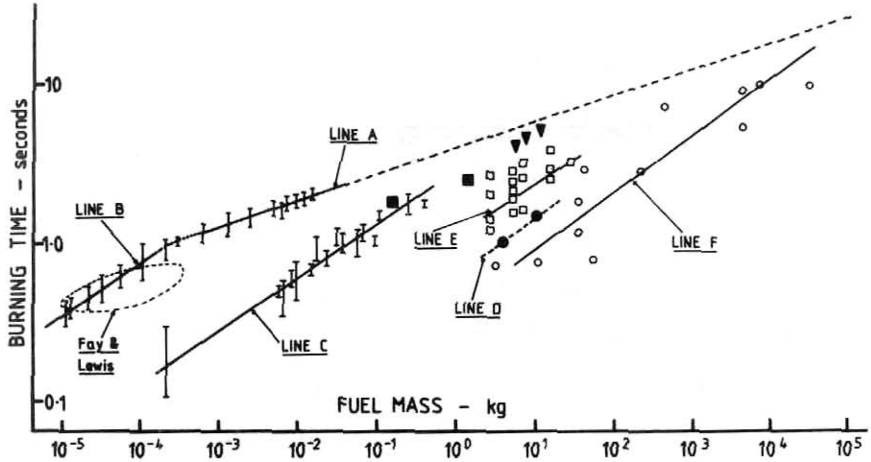
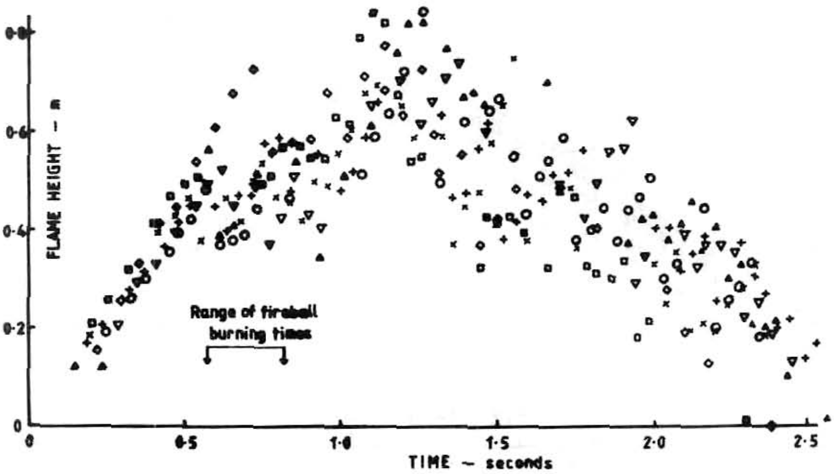


Fig. 2. Burning times versus fuel mass for soap bubble fireballs.
Lines A and B are drawn with slopes of 1/6 and 1/3 respectively.



Lines A&B: bubble fireballs, present work. Line C:toy balloons, present work. ●, Line D: pressurised propane, Baker, 1979. □, representative data from Hasegawa and Sato, *1977&1978*: Line E: Moorhouse and Pritchard correlation, 1982, of Hasegawa and Sato data for fuel mass < 3kg. Line F and ○ : data from rocket abort tests, *Gayle and Bransford, 1965*. ■, *Hardee et al, methane contained in* balloons, 1978. ▼, methane contained in meteorological balloons, present work.

Fig. 3. Summary of Fireball burning times versus fuel mass.



Disc diameter: 120mm; depth: 18mm; 7 runs: symbols, ○, ▽, ▲, +, ×, □, ◇, refer to separate experiments.

Fig. 4. Flame height versus time for disc bubbles.