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MEASUREMENTS OF SOME PARAMETERS OF THERMAL SPARKS WITH RESPECT TO THEIR ABILITY TO IGNITE AVIATION FUEL/AIR MIXTURES

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1 ABSTRACT

This report describes a method used to generate thermal sparks for experimental purposes, and methods by which parameters of the sparks such as speed,size and temperature were measured.

Values are given of the range of such parameters within these spark showers.

Titanium sparks were used almost exclusively, since it is particles of this metal which are found to be ejected during simulation tests to CFC joints.

Tests were then carried out in which titanium sparks and spark showers were injected into JP4/(AVTAG F40) mixtures with air. Single large sparks and dense showers of small sparks were found to be capable of causing ignition.

Tests were then repeated using ethylene/air mixtures, which were found to be more easily ignited by thermal sparks than the JP4/air mixtures.

2 INTRODUCTION

During a lightning simulation test, joints which carry a high current density may produce showers of 'thermal sparks'. This is particularly true of carbon fibre bolted joints, and questions as to the fuel ignition capabilities of such sparks are clearly important where 'wet-wings' are concerned.

The particular question is whether the testing standards which are now used are valid for the threat of thermal sparks, since such standards evolved by anticipating that the threat was from voltage sparks. In other words, will cameras detect all of those sparks, both voltage and thermal,which are a threat to fuel vapours, and are the defined test mixtures using ethylene or propane more likely to be ignited by such sparks than the 'worst' fuel/air mixture?

There is evidence to stimulate such concern. For example the ignition temperatures quoted for propane (470°C) and ethylene (425°C) are much higher than those of kerosine (210°C) and the higher hydrocarbons such as hexane (230°C), and in this sense the diagnostic gases appear less sensitive than the mixtures they are intended to protect. Although this question extends more directly to "Hot-Spot" ignition, which may be addressed at a later date, it may also affect the mechanism by which thermal sparks ignite fuel vapours. It is thermal spark mechanisms only which are considered in this report.

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3 THERMAL SPARK GENERATOR (TSG)

Creation of thermal spark showers is carried out by discharging a 80V/10,000μF capacitance into a titanium junction.The experimental arrangement by which these spark showers are produced is shown in Figure 1. The sparking occurs between a spinning titanium rod and a static titanium rod, with the relative motion of the two intended to prevent the junction from welding itself together during the discharge. Only a tiny fraction of the sparks which are produced enter the cell where the fuel vapour is contained, by passing through two narrow collimating slits.

4 MEASUREMENT OF SPARK PARAMETERS

4.1 Temperature

4.1.1 Measurement

Temperature is an obvious parameter to try to measure, since we would expect a cool particle to present less of an ignition risk than a hot particle

The approach to perform the measurement was based on two colour spectroscopy, whereby the intensity of colours in different parts of the spectrum is compared; in this case bands in the blue/violet and deep red regions of the spectrum separated by a diffraction grating, and incident onto photomultiplier tubes. The system is shown in Figure 2.

Titanium thermal sparks generated light which was collected by the fibres and fed to the colour analyser; both single, large sparks and showers of very many small sparks were subject to measurement. The results showed that there was a consistent ratio of blue/red in the emitted light (Figure 3), rarely varying by more than 10%.This implies a virtually constant temperature for these particles.

Temperature reference points were provided by fusing wires of Nickel (melting pt.1455°C) and Tungsten (mpt.3422°C) with current pulses. The results are summarised below.

TABLE 1
Red/Blue Ratios vs Temperature

	Temperature	Ratio	
Aluminium Sparks	not known	0.11-0.54	(Figure 5)
Titanium Sparks	not known	0.24-0.26	(Figure 3)
Fused Tungsten Filament	(3300-3422°C)	0.26. min	
Fused Nickel Filament	(1400-1455°C)	6.1. min	

It has been assumed here that the particles and the fused wires emit as black bodies, or that their emissivities are in the same ratio at the different colours.

4.1.2 Discussion on Temperature

Temperature estimates derived in this way for titanium particles indicate values in the range 3300-3600°C; the range including calibration errors. The temperature variation measured for different particles or showers is nearer to 150 °C

Titanium has a boiling point of 3422°C, which puts this value as an upper limit on the temperature of the particles, and the measured values are to this. It is possible that the explosive disintegration of the titanium spark occurs because the particle reaches, or slightly exceeds its boiling point, and then begins to 'boil' violently.

Aluminium sparks behaves very differently; they have a colour temperature which exhibits sudden changes and oscillations so that measured values range from 2600->4500 C, well above the aluminium boiling point (Figure 3). This behaviour is probably due to the fact that the particle is boiling, but in a manner which causes jets of burning vapour to be ejected, so that the particle then jets and spins, following a typically erratic path.

For both titanium and aluminium it seems that the particle itself is at or close to boiling point and therefore the same for all sparks of the same metal. Incendivity then depends on the rate at which energy is dumped into the particles track; this was discussed in Reference 1.

4.2 Particle Size

4.2.1 Measurement

4.2.1.1 Introduction

If the titanium spark particles are of virtually constant temperature then we have a relatively straightforward method of estimating their size, since the amount of light emitted by hot particles of a given material is a function of temperature, emissivity and size. Since temperature is eliminated as a variable the intensity of emitted light becomes a function of size only and proportional to the emitting surface area, if emissivity is constant.

The intensity of the emitted light can be measured in various ways, the best being to look at the signal voltage from a photomultiplier tube: study of the density of photographic images is also useful in providing rough comparisons, especially for comparing photographs of particles of known size with those seen during simulation testing.

4.2.1.2 Calibration

To provide a known reference point particles of known size need to be produced; in this case titanium particles 0.12mm in diameter were produced by fusing a short length of very fine titanium wire with a current pulse. The wire melts and shrinks to form a single burning bead. These 0.12mm diameter sparks burned with such brilliance that they were clearly larger than those generally seen during simulation testing, but they provide a calibration against which other particles can be referenced.

4.2.1.3 Photomultiplier Measurement

These relatively large calibration particles were compared with particles produced in more typical TSG showers by recording the light signal detected by a photomultiplier tube. A few spark showers produced particles whose signal range was typically 1/16-1/80 of the size of the calibration particles. However there were clearly particles even smaller, but as these tended to be emitted in showers with other much larger sparks it was difficult to ascribe a brightness to them.

Since the light emitted is assumed to be proportional to the area of the particle then we can deduce that the diameter of the unknown sparks produced by the TSG during these few showers lie largely in the range of 0.01 to 0.03mm, but with some even smaller particles.

4.2.1.4 Physical Method

It is also possible to collect a small proportion of the sparks in a shower by allowing them to strike an aluminium plate, so that a small proportion weld themselves to it. Size can then be determined with a travelling microscope. Whether a particle sticks to the plate or not may depend on its size, so that it is not a rigourous means of obtaining a population cross-section. 80% of the particles were 0.008-0.02mm in diameter, and <0.1% were greater than 0.1mm dia.

4.2.1.5 Photographic Method

It is useful to be able to look at a photograph of a spark shower and give an estimate of some of the particle sizes involved. Again it is possible to do this by relating the appearance of the 0.12mm diameter 'calibration' particles to those recorded on film by spark showers. It is not completely straightforward because particle speed is also involved, so that a slower particle of the same size as a faster one leaves a denser image track on film. However some of the effects of speed can be overcome using the "streak-camera" described in the next section. In general the larger the sparks the wider and denser is the image recorded on film. Their physical size is far too small to be resolved, so the image size of all particles is effectively determined by factors such as the lens, focussing, and the grain size of the film.

For example, some of the larger sparks seen during the testing of JP4 with spark showers (Section 6) appeared at f/5.6 to be approximately as bright as 0.12mm sparks photographed at f/16. This implies that the sparks seen during testing, which were found to pose an ignition hazard, have a diameter of approximately 0.04mm or greater. More typically the particles appear to be <0.02mm diameter.

4.2.2 Comments on Measured Particle Size

The camera system used to photograph most of the TSG sparks employed a lens set at f/5.6, 400 ASA film and an object distance of 300mm. In terms of sensitivity this makes it roughly equivalent to 3000 ASA f/4.7 system with a field of view of 0.5m at the plane of the object, which is a typical set up during simulation tests. Certainly photographed sparks during these tests vary over roughly the same visibility range as do particles from the TSG, although where large particles occur in real tests they are usually accompanied by such a large bright shower that it is difficult to distinguish individual particles.

During simulation tests where severe sparking occurs, the unsuing pitting may appear to be light. This is a further indication of how little material needs to be ejected to create a large spark shower.

4.3 Speed of the Particles

In this approach a simple 'streak' camera was constructed, by modifying an Olympus OMI camera and fitting a motor, so that film could be wound through the camera at constant speed whilst the shutter was held open. Otherwise the film, camera and lenses were as standard, and of the type used during simulation testing. In photographs taken using this the particle tracks, which are vertical in practice, appear to bend as the particles decelerate. Initially they are moving much faster than the film-to-image "streak velocity" and paths appear straight and nearly vertical; subsequent deceleration causes a bending effect which is visible in Figure 7 and from which the particle speed may be deduced.

In Figure 4 some typical particle paths are plotted, as a function of speed versus time and showing explosive disintegration as "*" where it occurs.

Those particles represented by a steep slope are decelerating very rapidly, and such particles are faint and generally die rapidly. Particles which have a lower deceleration rate are larger and brighter.

5 INCENDIVITY OF THERMAL SPARKS WITH RESPECT TO FUEL/AIR MIXTURES

5.1 Introduction

In this part of the report we discuss some less abstract, aspects of the work, looking at whether particular titanium sparks or spark showers are liable to cause ignition to JP4.

For most of these fuel tests sparks showers were generated using the TSG described in Section 3.

5.2 Mixing of JP4/Air

Aviation fuels are complex mixtures. Their many constituent components exhibit various degrees of volatility and flamability and the collective product is then not nearly as well behaved or reproducible as a pure gas. For guidance the advice and works of HWG Wyeth (RAE Farnborough) have been greatly appreciated. As Crouch (Reference 2) and others have pointed out, fractional distillation can occur from a liquid fuel, so that for example the drawing off of fuel vapour from a liquid headspace slowly reduces the fraction of volatiles. For these tests therefore the fuel was metered and transferred only in liquid form, and for each test a given volume of liquid fuel was allowed to come into equilibrium with the fixed volume of air in the test cell. The remaining liquid was discarded after each test. To further reduce fractional distillation effects the initial 20 litres of fuel was split into many small volumes so that no volume of fuel was subjected to many repeated exposures to air and loss of its volatile components. An unopened container had an RVP of 20, whilst one which had suffered repeated exposure to the air (more than that to which such a volume would be subjected in practice) had a slightly reduced RVP of 19.

Figure 5 shows the apparatus built to create the equilibrium fuel/air mixture. An air circulator blows air over the surface of the fuel and recirculates it through the test cell, keeping the largely unevaporated liquid isolated from the test cell, and from the risk of ignition.

The system has the advantage that equilibrium is achieved quickly; a gas analysis system within the cell showed that the system reached 90% of its equilibrium richness within 60 seconds for a relatively weak equilibrium mixture. For the tests a standard equilibrating time of 10 minutes was used.

5.3 Testing With Voltage Sparks

Initially the fuel/air mixtures were tested by ignition with voltage sparks to establish how the most flammable mixtures were created and also to compare ignition energies with those of Crouch

The method of determining spark energy was essentially that in Reference 3, although corrections were necessary as the breakdown voltage of a fuel/air mixture was higher than that of air.

The determination of ignitability was a little crude. Sparks of a defined energy were applied to the mixtures, 10 over a period of approximately 30 seconds. If an ignition occured then a (v) was designated, if not a (x) and these symbols are plotted against energy and mixture in Figure 6 The mixture is given as the percentage of the total volume taken up by liquid.

Given the statistical nature of this approach, results agree fairly well with those of Crouch.

5.4 Thermal Sparks Generator and Test Set up

This was described earlier and was shown in Figure 1. The collimetor was designed not only to limit the sparks to those travelling vertically but also to act as a 'quench' to prevent flame fronts created outside the slit from propagating back into the test cell.

The test procedure was to add the appropriate amount of liquid fuel into the reservoir, seal the apparatus and allow the air circulator to operate for 10 minutes (see Figure 5). Thermal spark showers were then injected into the mixture which was at the same time filmed using the "streak camera". Two useful film speeds were available, these provided an effective speed of the field of view of 1.8 or 4.5m/second relative to the camera. At the faster speed only 2 or 3 events could be captured on 36 exposure film, so there were time and cost penalties here and most shots are carried out at 1.8m/second. Frequent remixing of the vapour, changing of films and tuning of the TSG meant that the programme did not permit a large number of shots to be made.

6 RESULTS

The results of the programme are assessed by looking at the streak camera results for each of the fuel mixture tests, and identifying differences between those showers which did, or did not, cause ignition. Mixtures covered the range .22% to 1.1%, and in all over 80 spark showers of notable size were discharged. The 13 ignitions which did occur have been split into three classes as follows, and examples of each are shown in Figure 7:

6.1 Ignition by a Single Large Particle

This event was observed with certainty four times:

a) by a massive (~0.1mm dia) particle igniting a .35% mixture.
b) twice by a smaller, but still relatively large particle (~0.04mm) to a .4% mixture.
c) once by a large spark of undefined size (recorded on video) to a .4% mixture.

In all these cases ignition occured when the particle was travelling relatively slowly (< 1 metre/sec), and on two occasions this was because the particle had struck a wall.

6.2 Ignition by a Dense Shower of Particles

There were several occasions where ignition occured during a shower in which no particularly large sparks were present, but in which there was a shower of perhaps 15-25 particles, with high local spark density.

This occured: a) Twice to a .31% mixture.
b) Twice to a .40% mixture.

Dense showers were a fairly frequent occurrence during the tests to all the mixtures, but did not always cause ignition. It was difficult to see why one shower ignited, whereas another equal or even apparently larger shower, did not.

6.3 Spurious Ignitions of Unattributed Cause

The remaining ignitions were curious in that they occurred without any apparent cause, although always a short time after a spark shower had occurred .

One of the possible causes is that ignition occured within the volume between the collimating slits, so that an ignition developed within this space, and propagate through the narrow exit slit, failing to quench. Alternatively a single large particle might have stopped at or just above the slit exit and caused ignition, since there is 1mm above the slit which is blind to the camera.

6.4 Large Sparks and Spark Showers which did not cause Ignition

No ignitions whatsoever occurred in the 15 showers generated into .55%, .62% and 1.1% mixtures. Other large particles and showers which appeared similar to those which caused ignition, did not cause ignition. A well defined pattern is therefore difficult to establish; but Table 2 summarises the results.

TABLE 2

FUEL %	
.22	XXXXXXX
.31	XXXXXXX
.31	XXXXXXSS
.35	XXXXX?L
.40	X ? S
.40	S
.40	XXXXXXX??LL
.43	X X X ? ?
.55	X X X X X X
.62	XXXXXXXXX
1.1	XXXXXXXXXX

Summary of the ignitions which occurred to JP4/Air mixtures.
S= Spark Shower initiation
L= Large single spark initiation
?= Undefined initiation type
X= Sparks/Shower not igniting

7 IGNITION OF ETHYLENE BY THERMAL SPARKS

The exercise of injecting spark showers of the type used for JP4 is repeated here for ethylene to attempt a correlation of their ignitabilities by thermal sparks. It has previously been noted that ethylene is far more sensitive than fuel in detecting voltage sparks (References 2and 3).

Because it was anticipated from this that the ethylene had greater sensitivity, the size of the slot was reduced to 3 small holes less than 0.5mm in diameter, to improve the quenching performance of the slit, and to reduce the number of particles entering the cell as well as the width of the showers.

Eleven showers of relatively small sparks were produced, of which 2 caused ignition. One was caused by a single particle igniting the gas the second was caused by a group of particles.

7.1 Discussion

The spark showers and particles which ignited ethylene/air are smaller than those required to ignite JP4/air although it is difficult to be quantitative. The single particle which ignited the ethylene/air mixture is perhaps $^1/_2$ - $^1/_3$rd the diameter of the smallest single spark which ignited a JP4/air mixture, simply on the basis of visual assessment of image density.

However spark showers which do not ignite the mixture are clearly visible on film suggesting that cameras are a more sensitive technique - so long as the source of sparks can be anticipated, viewed and sharp focus achieved.

8 CONCLUSIONS

Temperature of aluminium and titanium thermal sparks appears to be close to the boiling point of the metals, and for aluminium jetting of vapour appears to occur from the spark.

A thermal spark generator has been built to produce showers of thermal sparks from a current carrying contact; such particles are found to be emitted at speeds of at least a few tens of metres per second, decelerating rapidly to perhaps only a few metres per second before disintegrating. Smaller particles are generated faster and last for a shorter time.

Size of the particles produced is commonly the range 0.005mm diameter to 0.05mm diameter.

A JP4/air mixture is created by recirculating the air headspace rapidly over a metered fuel reservoir to achieve equilibrium. Approximate minimum ignition energies are slightly less than those quoted by Crouch.

Ignition of fuel mixture can occur from the titanium thermal spark showers; either by large, slow single sparks estimated to be ≥0.04mm in diameter, or by a dense showers of smaller sparks.

Ethylene appears to be more easily ignited by thermal sparks than is JP4.

For detecting thermal sparks the defined photographic techniques are more sensitive than gas testing using ethylene (and much more sensitive than using fuel), but only so long as observed sparks can be gauranteed to be in focus.

9 REFERENCES

1. Haigh, Hardwick, Baldwin. Fuel Ignition Hazards from Thermal Sparks ICOLSE 1989. Bath, U.K.
2. Crouch Minimum Ignition levels of aircraft fuel constituents to lightning related ignition sources. ICOLSE 1986. Dayton.
3. Haigh, Baldwin, Banks. The detectability of voltage sparks by flammable gas and optical techniques. ICOLSE 1988. Oklahoma City.

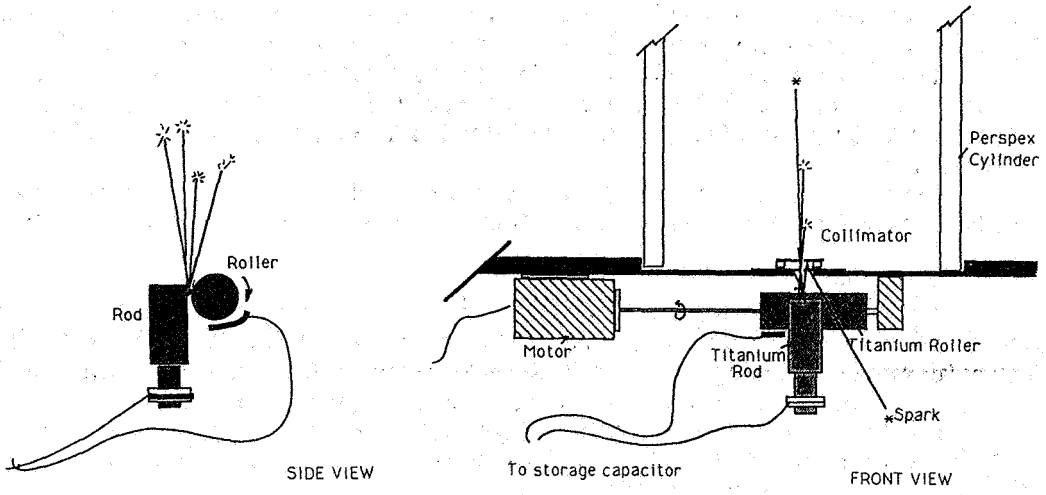

FIGURE 1

Generation of Titanium Thermal Sparks

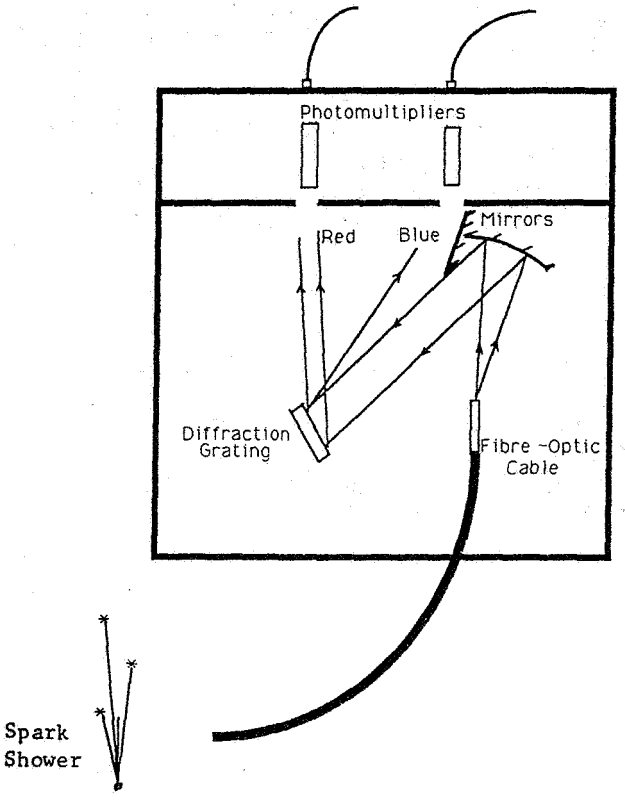

FIGURE 2

Measurement of Spark Temperature

TITANIUM SPARK SHOWER

ALUMINIUM SPARK SHOWER

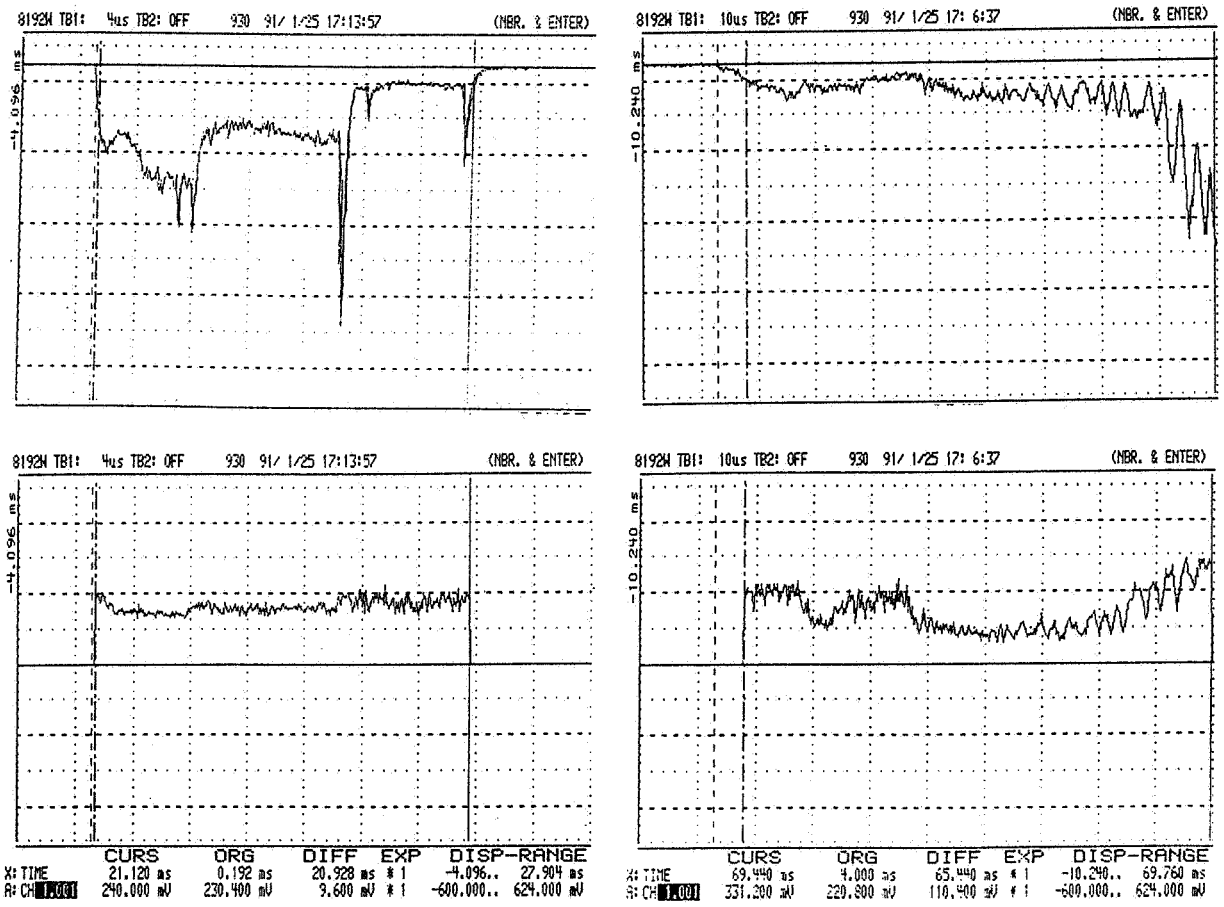

FIGURE 3

Recorded signals during the measurements of spark temperature
Upper Trace: Red Colour Signal (-ve going)
Lower Trace: Red/Blue Ratio (+ve going)

Left hand traces are for a Titanium spark shower, right hand for Aluminium.

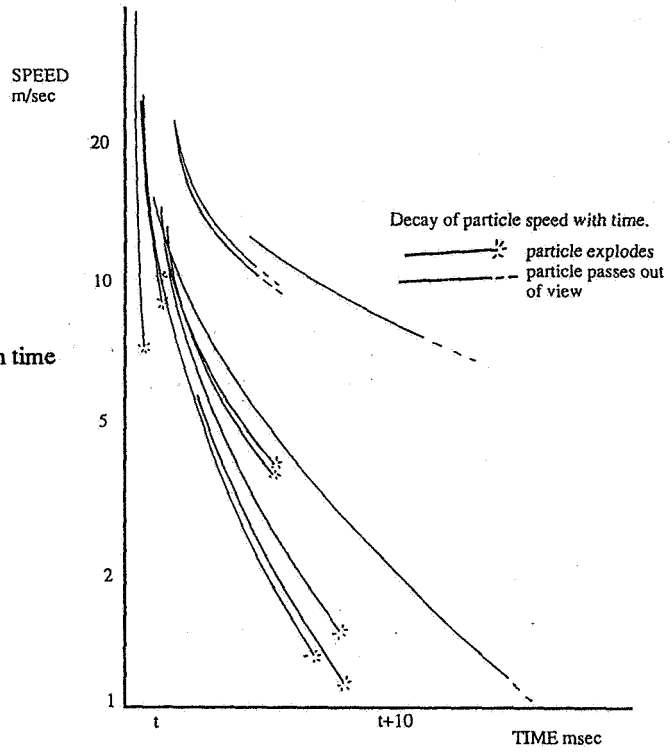

FIGURE 4

Decay of spark particle speed with time

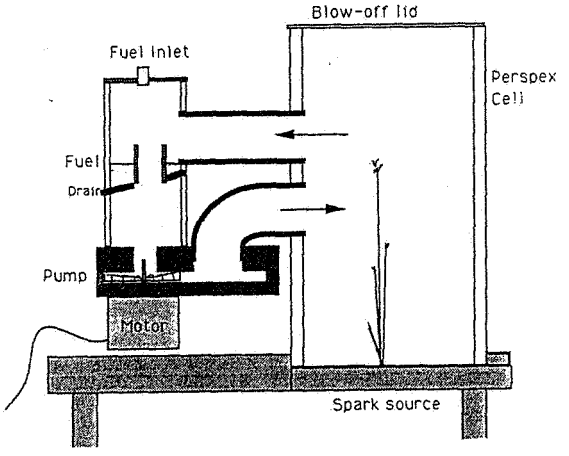

FIGURE 5

Generation of Fuel/Air Mixture

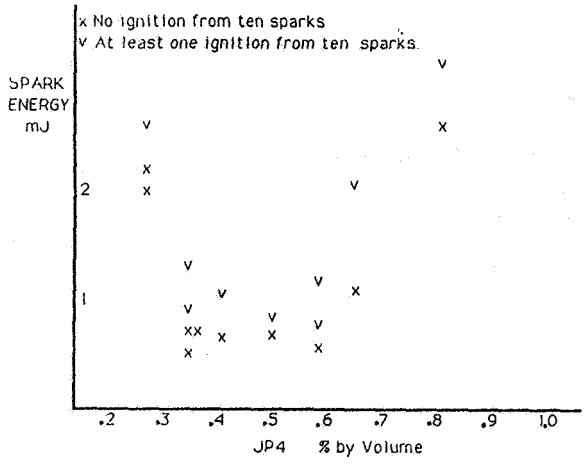

FIGURE 6

Ignition of JP4/Air mixtures of various concentrations by low energy voltage sparks.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

FIGURE 7

Three typical ignition sequences recorded by the Streak Camera. (JP4 Fuel)

The events are photographed through a wide slit, and the field of view appears as if it is moving rapidly from right to left.
Ignited gas regions appear as a fairly uniform glow.

TOP LEFT: Ignition by a single large particle.
LOWER LEFT: Ignition by a dense local shower.
LOWER RIGHT: A "spurious" ignition.