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OFFSHORE GAS DETECTOR SITING CRITERION INVESTIGATION OF DETECTOR SPACING

by

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EXECUTIVE SUMMARY

A possible strategy for siting flammable gas detectors on offshore oil and gas installations rests on the hypothesis that if a flammable gas cloud up to 6 m in length is ignited it will not produce flame speeds greater than 100 m/sec and damaging overpressures. These overpressures are deemed to be in excess of 150 mbar. This report assesses whether this hypothesis can justifiably be concluded from the experimental work on which it is based, and in light of other recent work in this field. It also explores its sensitivity to influencing factors such as gas species and mixture concentration, blockage characteristics and module size, possible overpressure values, ignition source and gas temperature.

The report finds that a stoichiometric 6 metre long methane or propane cloud, ignited by a point source will not achieve flame speeds greater than 100m/sec in methane and 125 m/sec in propane:

i) in a large unconfined volume with and without obstructions

ii) in a confined vented volume with levels of obstruction represented by blockage ratios up to 0.3 or 0.4.

Overpressure resulting from the above flame speeds will be less than 150 mbar. In situations where a high degree of confinement and obstacles exist, flame speeds may exceed 125 m/sec within 6 metres of ignition. Therefore gas detection should be increased as appropriate.

The conclusions above will be valid for mixtures of flammable gas species likely to be found in large quantities offshore.

Higher flame speeds and overpressures than above may be generated if more energetic ignition sources exist.

In cases of greater confinement or constriction than above, higher flame speeds or overpressures may occur.

This study has not considered the issues of how quickly a gas detected alarm would occur or how quickly effective mitigating actions would be taken. Response times of gas detectors, expected release rates and alarm thresholds are important matters which should be considered before a gas detector siting criterion is finalised

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OFFSHORE GAS DETECTOR SITING CRITERION
INVESTIGATION OF DETECTOR SPACING

MARCH 1993

1. INTRODUCTION

This study was undertaken at the request of the Health and Safety Executive and addresses the scope of work set out in Lloyd's Register of Shipping Proposal POG-16 of May 1992.

A hypothesis has been put forward that if a flammable gas cloud up to 6 m in length is ignited, it will not produce flame speeds greater than 100 m/sec or damaging overpressures. A damaging overpressure is deemed to be one in excess of 150 mbar. On this basis a regime for siting gas detectors on offshore oil and gas installations has been proposed, which locates detectors on a three dimensional grid with 5 m spacing, with alarm levels set at 20% and 60% LEL.

This report assesses whether this hypothesis can justifiably be concluded from the experimental work on which it is based, and in light of other recent work in this field It also explores its sensitivity to influencing factors such as gas species and mixture concentration, blockage characteristics and module size, possible overpressure values, ignition source and gas temperature

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2. MAIN REFERENCE "CONCENTRATION EFFECTS ON FLAME ACCELERATION BY OBSTACLES IN LARGE-SCALE METHANE-AIR AND PROPANE-AIR VENTED EXPLOSION." HJERTAGER B H ET AL [1]

This work was carried out during the early eighties in a 50 m^3 explosions test rig at Raufuss in Norway. Blast overpressures resulting from explosions in methane-air and propane-air mixtures were measured over a range of flammable gas concentrations. The effects of obstacles on flame speeds and overpressures as the flame front propagated through the test rig are related to gas flow velocity ahead of the flame. As a flame front propagates through the unburnt gas it acts as a porous piston which is pushed forward by the expansion of the burnt gas behind it. Due to the inertia of the unburnt gas a pressure wave is generated whose magnitude is related to flame speed. Obstacles ahead of the flame can create turbulence which increase the surface area of the flame front; the efficiency of combustion and hence flame speed and overpressure. The test work was carried out to investigate combustion over the full length of the rig rather than over the first 6 m specifically.

In this section, figure numbers refer to those in this reference. It is intended that this report be read in conjunction with the above paper. Figures and Tables included in this report will be identified as they arise.

2.1 Experimental Rig

The experimental rig consisted of a 2.5 m diameter steel tube of length 10 m. Annular rings blocked 30% of the tube apperture at five positions along the tube. Attached to the closed end of the tube was a 0.45 m diameter by 4.5 m long ignition tube which could be used as a jetted ignition source. This facility was not used in these tests but does not appear to have been isolated from the main rig. It is not possible to quantify its effect on the results but it may have contributed to scatter in the data.

Plastic film was used to cover the open end of the tube whilst filling with gas. This was removed just prior to ignition and may have led to scatter in measurements taken at the end of the tube due to dilution of the test gas. A single fuse head (point ignition) or array of 19 fuse heads (planar ignition) were used to ignite the gas mixture. Fuse heads would not provide a repeatable ignition source due to variations in the characteristics of individual heads. A high energy spark may give better reproducibility, however it would be difficult to fabricate a planar spark source. Later work by Hjertager [14] indicated that there is little difference between the two types of source

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This particular design of rig appears to have evolved from earlier work carried out to investigate combustion in pipes and tubes. The effect of roughening the tube walls has a marked effect on flame speeds and this principle has been extended to this large diameter tubular rig in which the rings give the roughening effect.

2.2 Experimental Results

2.2.1 Peak Overpressures and Terminal Flame Speeds

Peak overpressures at the tube outlet and flame speeds are plotted against gas concentration, for both propane and methane (Figures 3, 4, 5 & 6). Overpressures produced by propane are approximately twice those of methane over their respective flammability ranges but flame speeds in each gas are generally similar. There is one exception where the propane flame speed rises to a peak of 800 m/sec at stoichiometric concentration after planar ignition. This peak is attributed to the higher reactivity and smaller ignition delay of propane which displays an increased tendency towards transition to detonation. At other concentrations flame speeds are again similar to those of methane.

Planar ignition in both gases gives flame speeds and peak overpressure a factor of two higher than those resulting from point ignition. Point ignition in both propane and methane shows less well defined peaks in overpressure at stoic' conditions, with greater scatter in the results. Methane gives a peak overpressure of 2.5 bar at 9.5% v/v but the corresponding flame speed data shows no clear peak.

The results are within the accepted flammability ranges for both propane and methane (5% to 15% v/v methane and 2.3% to 9% v/v propane). Stoichiometric concentrations for methane and propane are shown to be 9.5% v/v and 4.5% v/v respectively.

The region between LEL and stoic' concentration is the main area of interest in this study Scatter in the data is less at the lower concentrations which suggests that a higher degree of confidence

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may be placed in these results. Generally propane presents the greatest hazard in the context of this report, especially at low concentrations. Overpressures in propane in excess of 1 barg occur at concentrations of less than 4% v/v whereas methane concentrations must be in excess of 8% v/v to give the same overpressure. Overpressures measured along the tube are not presented in this paper and it is not possible to comment on the development of pressure down its length during an ignition. However some relevant results are presented in other references from which conclusions may be drawn.

2.2.2 External Overpressures

Although overpressures at the tube exit show a marked degree of scatter, measurements 10 m from the exit show a smooth variation as concentration is increased from LEL to UEL, peaking at stoic' concentration. The marked peak in propane flame speed at stoic' conditions for planar ignition is again not apparent in these overpressure measurements.

2.2.3 Flame Speeds and Turbulence Levels

Flame speeds measured by means of ionisation probes on the centreline of the tube are compared with gas velocity measurements from hot wire probes on the centreline and in the shear layer behind the obstacles. Out of 14 instrumented tests only four gave satisfactory hot wire measurements which can be compared with flame speeds. Two of these tests involve point ignition in propane and methane at stoic' conditions, and two involve planar ignition slightly above stoic'. Unfortunately no data is presented for lower concentrations.

Flame speeds are derived by measuring the distance between successive probes and dividing by the time taken for the flame to travel between them. Figures (11 to 18) show flame speeds versus distance from ignition, in which flame speed measurement positions are half way between the ionisation probes It appears from the presented results that the second probe, 3 45 metres from the ignition point was not operational

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This implies that the distance over which the flame speed was measured was 2 rather than 1 metres, with a corresponding decrease in accuracy.

Hot wire measurements show gas flow velocity up to the point where the flame front passes the probe, after which the wire is burnt out. The expression used for derivation of turbulence velocities is standard for single wire measurements.

Figures (9 and 10) show hot wire probe output against time for a point-ignited propane test at 4.5% concentration. Values of X/L for the first two points shown on the graphs in figure (10) do not correspond to actual probe positions, and it has been assumed that the data corresponds to the first four probes. The features to note are:

i) in the early stages of combustion, up to 2.45 metres from the ignition point, the flame front takes twice the time to reach the first shear layer probe as the centre line probe. This suggests a spherically expanding flame front exists at this early stage.

ii) turbulence levels are thereafter much higher in the shear layer, implying more efficient combustion in this area and hence an accelerating flame front

iii) mean flow velocities in the shear layer at the end of the tube are lower than those on the centre line. Also, turbulent fluctuations peak at centre line velocities. The high turbulence fluctuations could, as stated, be approaching levels at which turbulence quenching occurs.

iv) at 6.4 metres from the ignition point the flow velocity on the centre line is 100 m/sec.

Figures (11 to 14) give flame velocity, gas-flow velocity and turbulence versus distance for propane and methane at stoic' concentration, after point ignition. The results for methane and propane are similar and flow velocities are approximately 20 m/sec lower than the flame velocities at each point. At 6 metres from ignition flame speeds for methane and propane are 100 and 125 m/sec respectively, rising from 80 and 100 m/sec at 5 m

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Planar ignition gives higher flame and flow velocities in both gases (Figures 15 to 18). Flame speeds in methane are unclear from the results but appear to be in the region of 200 to 300 m/sec at 6 m and propane flame speeds approximately 250 m/sec. Other work by Hjertager [11] with planar ignited methane suggests unstable flame propagation due to the flame burning back to unburnt pockets of gas behind the obstacles. This may account for the wide scatter in the methane flame speed measurements. In this case the gases are slightly above stoic' concentration and propane shows less scatter in results than methane. In Figure (15) the centre line flow velocity appears to be higher than the flame velocity. It is possible that this anomaly is due to temperature variations in the gas. As the gas is compressed its temperature will rise and unless the probes have been calibrated over the full range of flow conditions some offset in the measurements will occur.

2.4 Summary of Main Reference

Based on the results presented above, point ignition of a stoichiometric methane gas cloud in a confined volume with 30% blockage will result in flame speeds up to 100 m/sec, 6 m from ignition. Similar ignition in a propane cloud will result in flame speeds of 120 m/sec. Planar ignition results in flame speeds of 200 to 300 m/sec in both gases at 6 m. However, this test rig cannot be considered to provide a generalised form of turbulent flow. The annular rings, although providing 30% blockage leave an unobstructed zone 2.06 m diameter down the centre of the rig. As the flame front progresses down the tube, the turbulent wake will expand towards the centreline. In the early stages of combustion the flame front will see no obstructions, and turbulence generation in the shear layer will not influence the burning rate at the centreline. Overpressures inside the rig or pressure/time profiles are not presented and it is not possible to comment on the pressure levels in the early stages of the tests.

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3. SUMMARIES OF SUPPORTING REFERENCES

3.1 The Influence of Turbulence on the Rate of Turbulent Burning. Abdel-Gayed et al [2]

Microscopic burning processes are discussed with reference to laminar burning of eddies and chemical kinetics. The process of turbulence quenching of flames, atmospheric burning and explosions is investigated and compared with experimental measurements in a small scale rig. A threshold level for turbulence intensity is determined above which the burning velocity is observed to decrease. This value is expressed in terms of the ratio of turbulent to laminar burning velocity.

3.2 Venting of Turbulent Gas Explosions in a 50 m^3 Chamber. Eckhoff et al [4]

This paper is referenced to illustrate the effects of sharp edged obstacles on explosions. The test work was carried out in the 50 m^3 test rig but in this case the ignition tube was used to initiate the explosion. No obstructions were placed in the main rig and the effects of jetted ignition was observed on stoic' propane gas clouds. No data was presented for the ignition in the first 6 m of the main tube.

Sharp edged obstacles were placed at intervals inside the ignition tube and various sizes of orifice were placed at its end. Transition to detonation was achieved for some obstacle configurations in which pressures of up to 18 bar were generated. Pressures measured in the main chamber ranged from 0.3 to 3 bar depending on the ignition tube configuration.

The tests demonstrate the effect of obstacles on ignition characteristics in a smaller diameter tube, and of jetted ignition into a quiescent stoichiometric gas cloud. They do not illustrate the effects of turbulence downstream of the flame front in the main rig.

3.3 The Flammability Limits of Gases, Vapours and Dusts: Theory and Experiment. Hertzberg 1981 [5]

The paper presents data on the flammability limits of methane, hydrogen, acetylene and ammonia air mixtures These differ slightly from those measured in Reference [1], but the difference is not significant Small

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differences in flammability limits of upward burning and horizontally burning gases are noted and attributed to buoyancy of the flames. However, these will not affect the results of this study.

3.4 Simulation of Transient Compressible Turbulent Reactive Flows. Hjertager et al [6]

This paper gives an explanation of the mathematical model used to simulate planar ignited methane explosions in the 50 m^3 test rig. Modelled pressures at the ignition and exit ends of the tube are shown to be similar in profile but 30% higher than those measured by Moen (Reference [11]). The pressure decay was also predicted to be longer than that measured. This was attributed to the fact that the final obstruction ring, made of plywood on the experimental rig, was destroyed in each test giving faster pressure decay than expected at the end of the tube (this fact was not mentioned in Moen's reference [11]).

Pressure, flame contours and reaction rate are predicted as the flame progresses down the tube. The pressure is seen to achieve a level of 0.4 bar, 6 metres from ignition. The prediction suggests that acceleration occurs as the flame front passes each obstacle although this effect is not so apparent from actual measurements because the distribution of data points is fairly coarse. However, both prediction and measurement indicates that flame speeds will be between 300 and 500 m/sec at 6 m.

3.5 Numerical Simulations of Turbulent Flame and Pressure Development in Gas Explosions. Hjertager 1981 [7]

The basis of a mathematical and computational model for turbulent flame propagation is described. This is used in the FLACS computer code and predictions from it are compared with measurement of peak overpressure in the 50m^3 test rig. Both planar and jet ignition sources were modelled for methane and propane-air mixtures. Peak overpressures, both measured and predicted, were generally high (>200 mbar) and the paper does not provide data relevant to the early stages of combustion

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3.6 Flame Acceleration of Propane-Air in a Large-Scale Obstructed Tube. Hjertager et al [8]

These tests were carried out in the 50 m^3 test rig using propane gas and a planar ignition source. A range of blockage ratios and number of rings was used to investigate their effect on overpressure and flame speed. No flow velocities were measured but flame speeds were determined on the centreline and at the shear layer.

Time of arrival of the flame front versus distance, for three identical tests, with a blockage ratio of 0.3 and five rings (as in the main reference [1]) show a variation in arrival time of up to 60 msec, 6 m from the ignition point. (Figure 1, this report). In at least one test the flame at the shear layer exited the tube before that on the centreline. The relevant conclusion to be drawn from these results is that from test to test there may be a wide variation in results and individual test results should be treated with caution. However, the maximum centreline flame speed appears consistently to have been achieved after five metres travel down the tube in each case. No other information is presented for the early stages of ignition but generally these results correspond to relevant tests in the main reference [1].

3.7 Explosions in Vessels: Recent Results. Lee [10]

This paper quotes the results of tests in tubes 63 to 150 mm diameter and in a small rectangular vessel 1.2 m long, which investigate flammability limits and stoichiometric mixtures of methane, propane and hydrogen. Flame acceleration was found to be highly dependent on the Reynolds number of flow in the obstacles ahead of the flame. Peak flame speeds in methane were found to occur towards the lean side of the stoic' concentration and for propane towards the rich side. The scale is small and the results cannot be extrapolated to a large scale tube burning situation.

3.8 Pressure Development due to Turbulent Flame Propagation in Large-Scale Methane-Air Explosions. Moen et al [11]

These tests were carried out in the 50 m^3 rig using methane gas and a planar ignition source. With no obstacles present the average overpressure measured was less than 0.1 bar, the peak value being 0.12 bar. Six orifice plates of blockage ratio of 0.3 resulted in an average overpressure of 5.53 bar and peak of 8 86 bar inside the tube which represents a 30% increase on overpressures measured in reference [1] using five plates

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The most relevant data in the report shows pressure-time profiles at various points down the tube for a blockage ratio of 0.3, with 5 annular plates, as shown in Figure 2, this report. Correlation of time of arrival of the flame front at the centreline ionisation probes with the pressure profile (Figure 3, this report), indicates that the flame front reaches a maximum velocity of 300 m/sec (as in the main paper) and pressure 0.25 bar. This is achieved 140 msec after ignition when the flame front has travelled 5 m down the tube. After this position the velocity remained fairly constant.
Data for other blockage/ring combinations indicate that flames are still accelerating, up to 5 m from the source. Generally, all flames have achieved their terminal speeds at or near 6 metres distance from the ignition point.

It is acknowledged in this report that removal of the polythene sheet from the end of the tube before ignition affected the results and that the fuse heads may not provide a reproducible source of ignition.

Pressure profiles for high blockage ratios included several strong peaks attributed to the combustion of pockets of gas trapped behind obstacles in the first half of the tube. This effect could explain the wide scatter in the data shown in Figure (17), Reference [1] for planar ignition of methane. The paper again confirms that planar ignition gives relatively high flame speeds and overpressures and that the flame has accelerated to its maximum speed 6 m from the ignition point.

3.9 Transmission of an Explosion through an Orifice. Thibault et al [12]

The paper examines the relationship between burning velocity and quenching diameter for methane, propane, ethylene and hydrogen. Experiments carried out in a small diameter ignition tube were compared to the large scale tests of Eckhoff et al [4]. Effects of Joule-Thomson cooling and Mach compression in a sonic jet are investigated and related to the transmission of an ignition through an orifice.

3.10 Summary of Supporting References

The supporting references are concerned with three main topics, namely, the effects of sharp edged obstacles on turbulence and burning rate, flammability limits and stoichiometry and turbulence quenching

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References [4, 5, 8 and 11] confirm the effect of sharp edged obstacles on flame speed and overpressure. They also confirm stoichiometric mixture concentrations measured in the main reference.

References [6 and 7] demonstrate the effect of turbulence on burning rate and references [2 and 4] investigate turbulence quenching.

Reference [11] provides confirmation that in the event of planar ignition of methane, flame speeds will exceed 200 m/sec within 6 m of the ignition and overpressures will be in the order of 0.25 bar.

Although the supporting references confirm the points raised in the main reference the majority of large scale results were obtained in the 50 m^3 test rig, hence characteristics peculiar to this rig may not have been isolated. Also they do not provide supporting data on flame speeds and overpressures over the first 6 m after point ignition

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4. SUMMARIES OF OTHER RELEVANT REFERENCES

4.1 The Effect of Obstacle Arrays on the Smooth Combustion of Large Premixed Gas/Air Clouds. Harrison et al [13]

These tests provide data on flame speeds and overpressures generated in large unconfined premixed natural gas (96% methane, 4% ethane) air clouds in the presence of obstructions. Sufficient detailed information is provided to determine flame speeds over the first 6 m of the rig.

The rig consisted of a 30 m long by 10 m high wedge shape of volume 4000 m^3 (Figure 4, this report). Wooden shuttering was used to fabricate the vertical walls, the end and roof being covered with polythene sheet. Obstacles consisting of 0.315 m diameter tubes, were set in horizontal arrays providing 40% blockage. Up to six arrays were set up with 2, 4 or 5.8 m spacing and 5 or 10 pipes in each array. Eleven tests were conducted using propane-air or natural gas-air mixtures, with point ignition at the apex of the rig sector.

Initially several tests were carried out with no obstructions in the rig, producing flame speeds in natural gas of 8 to 9 m/sec and overpressures of 5 mbar. Similar tests in propane gave flame speeds of 30 m/sec and overpressures of 10 to 15 mbar. Subsequent tests using 3 arrays of 10 tubes set 2, 4 or 5.8 m apart indicate that flame speeds in methane did not exceed 70 m/sec at 6 m from ignition (Figure 5, this report). These tests produced overpressures between 30 and 63 mbar, at approximately 6 m from ignition.

A maximum flame speed of 120 m/sec and overpressure of 208 mbar resulted from 6 arrays of 10 tubes set 2 m apart. The flame is stated to accelerate progressively through the obstacles which, assuming a similar rate of acceleration as in the other tests, implies that at a distance of 6 m (i.e. half way through the obstacle array) the flame speeds would have been well below 100 m/sec.

The variation of flame speeds with distance in a stoic' methane mixture with 3 arrays of 10 tubes 4 m apart is related to pressure, measured 15 m from the ignition point (Figure 6, this report). A slight increase in pressure as the flame front passes each obstacle is apparent but the overpressure did not exceed 70 mbar and flame speeds of 17 m/sec

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Tests using propane did not provide significantly higher flame speeds or overpressures. These tests, carried out in a large premixed, relatively unconfined cloud are analogous, over the first 6 m, to ignition of a small cloud (<10 m) in a large volume with low congestion.

Four tests were initiated by a jetted ignition from a chamber attached to the apex of the rig. Flame speeds up to 170 m/sec and overpressures up to 710 mbar were measured in the main rig. The flame speeds corresponded to the jet flame emerging from the chamber and were observed to decrease soon after emergence from the obstacle arrays. It appears that the jet flame persisted up to 5 m into the main rig, so no useful inferences can be drawn from these tests.

4.2 Gas Explosion Experiments in 1:33 and 1:5 Scale Offshore Separator and Compressor Modules Using Stoic' Homogeneous Fuel Air Clouds. Hjertager et al [14]

Scale models of the above modules were fabricated in which propane-air and methane-air explosions were initiated. Data obtained from the tests was used to evaluate the effects of scale and to validate concepts developed in the formulation of predictive models based on earlier idealised tests [1]. The 1:33 scale tests are not considered here as they are not applicable to the subject of this study.

Tests on the 1:5 scale models (8 m long by 2.5 m square) provide data on flame speeds and overpressures for a range of vent configurations and ignition positions. Totally enclosed, empty modules (volume 50 m^3) gave maximum overpressures of 120 mbar in propane-air and 30 mbar in methane-air mixtures. When obstacles were introduced (separator module blockage ratio 0.3, compressor module blockage ratio 0.1) overpressures over 150 mbar were measured for vent parameters ($A/V^{0.6}$) of 1.98 or lower (i.e. end walls open only, or module totally enclosed) (Figure 7, this report). All other vent configurations gave overpressures of less than 100 mbar. Propane flame speeds of between 50 and 100 m/sec were measured in the compressor module up to 6 m from ignition (blockage ratio 0.1). As the flame propagated through the module, away from the open end, the resistance to venting behind the flame increased due to the obstructions (Figure 8, this report). A significant rise in flame velocity at 7.5 m, in the lower part of the module is attributed to process equipment configuration.

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4.3 Understanding Vapour Cloud Explosions. Harris et al [15]

The paper begins by discussing explosion incidents involving hydrocarbon and other gases and explaining the processes which generate pressure in a combusting gas cloud. A theoretical model proposed by Kuhl [16] is referred to and a relationship between flame speed and overpressure developed from this work is presented. No details of the work to extend Kuhl's model are given however it is indicated that flame speeds of 100 m/sec are required to produce overpressures of 130 mbar i.e. less than the threshold value for structural damage (Figure 9, this report).

The report then discusses tests to study the combustion of stoic' gas-air mixtures of natural gas (92% methane, 4% ethane, 4% nitrogen), LPG, cyclohexane and ethylene, ignited by single spark. Initially mixtures were confined in 3 m radius (120 m^3) balloons and measured flame speeds did not indicate acceleration of the combustion front. Speeds of 7 m/sec were measured in methane, and 15 m/sec in ethylene.

Large scale tests were then carried out in a 45 m long, 3 m square rig, with only the rear wall and floor being solid constructions. The rig was covered with polythene sheet and gas mixtures were ignited by a single spark on the rear wall. Measured unobstructed flame speeds were in the range 8 to 19 m/sec, with natural gas again the least reactive and ethylene the most reactive gas. Natural gas flame speeds are similar to those reported during work on the combustion of LNG and LPG gas clouds after spillage on water [19].

In order to investigate the effect of obstacles, arrays of 180 mm tubes were arranged to give 40% blockage and spaced 1.5 m apart down the length of the rig. Initially only the first 22.5 m of the rig contained obstacle arrays and typical flame speeds of 20 m/sec were measured 6 m from ignition. Flame acceleration continued to the end of the arrays giving maximum speeds of 90 m/sec. After this they dropped back to less than 30 m/sec in the unobstructed region (Figure 10, this report).

Subsequent tests using natural gas-air and cyclohexane-air, in which the full length of the rig contained obstacles, resulted in flame speeds of 25 m/sec in natural gas-air and 35 m/sec in cyclohexane-air at 6 m from ignition (Figure 11, this report). Terminal flame speeds in natural gas-air were less than 100 m/sec giving an overpressure of approximately 100 mbar. However, cyclohexane-air mixtures gave flame speeds of 230 m/sec and overpressures of 700 mbar.

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Finally, tests were carried out in the 45 m rig with a 9 m long ignition chamber attached. Obstacle arrays were placed within this chamber to produce high speed flames which propagated into the unconfined section. No useful data is provided on flame speeds over the first 9 m in this chamber.

To summarise, point ignition of an unconfined stoichiometric gas-air mixture with or without turbulence-producing obstacle arrays did not produce flame speeds above 100 m/sec within 10 m of ignition. Consequently, overpressures were correspondingly small.

4.4 Similarity Analysis of Flame Driven Blast Waves With Real Equations of State. Kuhl [16]

The paper describes a model for the prediction of blast overpressures and flame burning velocities for infinitely thin, constant velocity one-dimensional blast waves in a methane/air cloud. Equations of state for the blast wave and a flame model are developed from which relationships between pressure ratio and burning velocity are produced. The velocities range from 1 to 100 m/sec and are assumed to be equivalent to the turbulent rather than laminar burning velocities. These correspond to overpressures of 1 mbar to 5 bar for point and planar combustion.

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5. DISCUSSION

Relevant results shown from the main reference and other supporting material are drawn together and summarised in Tables 1, 2 and 3. Table 1 refers to point ignition, Table 2 to planar ignition and Table 3 to jetted ignition. Gases such as cyclohexane and ethylene are included in Table 1 for comparison but are not considered further as they are unlikely to be found in significant quantities in an offshore environment.

Full scale explosion tests have been primarily concerned with maximum flame speeds and overpressures and have not concentrated on the first 6 m of combustion. However, the ignition of a small gas cloud in a large volume can be considered analogous to the early stages of combustion in a large unconfined cloud. Relevant data from such tests is therefore considered to be appropriate for this study. Similarly, confined explosion testing has concentrated on terminal flame speed and overpressure data and again relevant results covering the first 6 m after ignition have been extracted.

Of the three modes of ignition studied (point, planar and jetted), point ignition is considered to be the most likely to occur offshore. Planar ignition requires a very hot surface due to the high autoignition temperatures of methane and propane (540°C and 450°C respectively). Jetted ignition requires an earlier initiating event which implies that detection and shutdown systems will have already operated. For the above reasons, although planar and jetted ignition produce relatively high overpressures and flame speeds (Table 2 and 3) they are not considered further.

For gases with the reactivity of methane or propane point ignition in unconfined clouds gives flame speeds between 10 and 35 m/sec at 6 m from ignition. Fairly high levels of obstruction in unconfined clouds do not increase flame speeds above 120m/sec and overpressures remain correspondingly low. Confinement of the cloud results in flame speeds up to 100 m/sec in methane and 125 m/sec in propane at 6 m from ignition. Blockage provided by ring type obstacles in a 50 m^3 tube may not provide a good representation of obstructions in an offshore environment. However maximum flame speeds of 125 m/sec were measured in stoichiometric propane mixtures and are therefore considered to be conservative as this is typically the most reactive gas found offshore.

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Methane and natural gas are the least reactive of the hydrocarbon gases giving explosion overpressures of about half of those of propane and other LPG's at stoichiomertic concentrations. Little data are available for overpressures resulting from the initial 6 m of combustion only. However, large scale unconfined gas cloud explosion tests [13 and 15] indicate pressures between 20 and 50 mbar with peak overpressures rising to 70 mbar after further combustion. No overpressure data is available for confined vented explosions over 6 m from ignition, but flame speeds at this distance indicate acceptable values based on references [1, 15 and 16].

Natural gas has very similar properties to methane but its stoichiometric concentration in air is slightly higher than that of methane. The flammability limits of methane are 5% to 15% v/v in air and propane, 2 to 9% v/v. This implies that gas concentrations at which the detectors must operate (20% and 60% LEL) will be correspondingly lower for propane than for methane.

Flame speeds generated during unconfined tests in natural gas were found to be dependant on obstacle spacing over the first 6m. For a blockage ratio of 0.4 (Table 1, Ref [13]) flame speeds at 6 m are seen to decrease as the obstacle spacing increases. This effect is partially due to the acceleration of the flame front as it passes through the turbulent flow field behind each array. If the spacing between the arrays is sufficiently small the acceleration is maintained from obstacle to obstacle. However, if the spacing is large, the flame front decelerates again before impinging on the next array.

The mathematical modelling of gas cloud explosions [16] has been extended [15] to give a relationship between flame speed and overpressure (Figure 9 of this report). Further, a relationship between flame speed and burning velocity is put forward in [15] in which flame speeds up to 500 m/sec would correspond to burning velocities of 70 m/sec. This mathematical relationship should not be generally applied to all gas cloud explosion scenarios as the magnitude of burning velocity cannot be easily defined. For example Fairweather and Vasey [17] suggest turbulent burning velocities can be up to five times the laminar value. This would restrict the range of prediction in [15] to turbulent burning velocities of 2.25m/sec giving maximum flame speeds of 20 m/sec and overpressures of 5 mbar. However this restriction applies only to a totally confined or vented enclosure without obstacles. Predictions involving higher flame speeds and overpressures obviously require more complex modelling. Actual burning velocities are a matter of some conjecture and depend strongly on individual circumstances.

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The obstructions arrangement used by British Gas [15], consisting of horizontal arrays of 180 mm diameter pipes, spaced to give a blockage ratio of 0.4 and set 1.5 m apart is considered by them to be the optimum configuration giving the highest flame front acceleration. However, as pointed out in [18], idealised experiments designed to provide a relationship between peak overpressure and blockage do not necessarily provide data which can be related to all other test situations or actual scenarios. The data should only be used to support an underlying theoretical model which, if all physical processes are modelled correctly, can be used to extrapolate to a general situation.

This study has not considered the issues of how quickly a gas detected alarm would occur, or how quickly an effective mitigating action would be taken on an offshore installation. These are important matters which should be considered before a gas detector siting criterion is finalised. The time to alarm of a catalytic gas detector will depend on the time to build up a gas mixture in excess of the alarm threshold in the vicinity of the detector, and the detector response time.The response time of the (commonly used) catalytic type gas detector depends, inter alia, on the ambient concentration; the greater the concentration the faster the response. If a step change in concentration from 0 to 100% LEL occurred, a typical sensor might reach a first alarm output in 5 seconds. However when more realistic (steady) growth of ambient gas concentration takes place, and allowing for the obstruction to gas entry caused by weatherproof housings, it would be reasonable to expect a gas detector to give first alarm in 10 to 15 seconds.Within this time a gas cloud could feasibly grow to form a sphere of flammable mixture of diameter greater than 5 m, if the release rate were great enough. So in deciding a spacing distance for flammable gas detectors it is important that potential release rates should be taken into account.

In addition the usefulness of a gas alarm signal will depend on the time to then initiate mitigation measures and the time for these to take effect.

Fluid temperature is not considered an important parameter in this study. Normal produced fluid temperatures are sufficiently low for the gas to tend towards ambient temperature within a short time of release.

Contents

6. CONCLUSIONS

6.1 It can be concluded from the papers examined that a stoichiometric 6 m methane or propane gas cloud ignited by a point source will not achieve flame speeds greater than 100 m/sec in methane and 125 m/sec in propane:

i) in a large volume, with and without obstructions

ii) in a confined, vented volume with levels of obstruction represented by blockage ratios up to 0.3 or 0.4.

6.2 Overpressures resulting from the above flame speeds will be less than 150 mbar (i.e. the threshold for major structural damage).

6.3. Methane (natural gas) and propane are considered to be the most likely gases found offshore in significant quantities. Of these propane is the most reactive resulting in explosion overpressures of twice the magnitude of methane. Propane gives the greatest hazard at low concentrations as its LEL is approximately half that of methane.

6.4 Jetted or planar ignition of the gas cloud will result in flame speeds and overpressures above the damage threshold. These are not considered likely initiating events offshore. If however a large area, hot surface could arise (e.g. in a gas compression module) the level of gas detection should be increased as appropriate.

6.5 In a situation where a high degree of confinement and obstruction exists, flame speeds may exceed 125 m/sec within 6 m, therefore gas detection should be increased accordingly.

6.6 The above gas detector regime is considered appropriate for small scale leaks which are such that the gas cloud 60% LEL concentration boundary does not exceed the detector spacing, within the response time of the detector system.

6.7 The time to take effective mitigating action following a gas release and gas alarm is significant and should be taken into account in choosing an appropriate detector spacing distance.

Contents

7. LIST OF REFERENCES

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Contents

GAS	RIG	CONFINED	OBSTACLE TYPE	OBSTACLE SPACING (M)	NUMBER OBSTACLES ARRAYS	BLOCKAGE	MIXTURE % V/V IN AIR	FLAME SPEED @ 6M (M/SEC)	PEAK FLAME SPEED (M/SEC)	O/PRESS @ 6 M (MBAR)	O/PRESS PEAK (MBAR)	REF NO
METHANE	50 m³ TUBE	YES	RING	2	5	0.3	9.5	100	200	-	2500	1
PROPANE	"	YES	RING	2	5	0.3	4.5	125	200	-	4000	1
METHANE	4000 m³ WEDGE	NO	TUBE ARRAY	-	-	-	9.5	-	8 - 9	-	10-15	13
METHANE	"	NO	"	2	6	0.4	9.0	<120	120	-	208	13
METHANE	"	NO	"	2	3	0.4	11.6	18	49	30	55	13
METHANE	"	NO	"	4	3	0.4	9.7	12	51	30	63	13
METHANE	"	NO	"	5.8	3	0.4	10.0	11	50	20	30	13
PROPANE	"	NO	"	5.8	3	0.4	4.2	-	50	-	30	13
METHANE		YES	NONE	-	-	-	STOIC'	-	-	-	30	14
PROPANE	50 m³ SCALE MODEL	YES	"	-	-	-	STOIC'	-	-	-	120	14
METHANE		YES	PLANT	RANDOM	RANDOM	0.3	STOIC'	-	-	-	150	14
PROPANE		YES	"	"	"	0.1	STOIC'	50-100	800	-	400	14
NAT. GAS LPG	45 m³ Rect-angle	NO	NONE BOX/GRID	- RANDOM	- RANDOM	- 0.4	STOIC' STOIC'	- -	8-19 50-70	- -	- 30-70	15 15
CYCLO-HEXANE ETHYLENE	"	NO	"	"	"	0.4	STOIC'	-	200	-	800	15
CYCLO-HEXANE	" "	NO NO	TUBES "	1.5 1.5	15 30	0.4 0.4	STOIC' STOIC'	20 35	90 200	- -	- 700	15 15
NAT. GAS	"	NO	"	1.5	30	0.4	STOIC'	25	75	-	<100	15

TABLE 1 SUMMARY OF RESULTS FOR POINT IGNITION

Contents

GAS	RIG	CONFINED	OBSTACLE TYPE	OBSTACLE SPACING (M)	NUMBER OBSTACLES ARRAYS	BLOCKAGE	MIXTURE % V/V IN AIR	FLAME SPEED @ 6M (M/SEC)	PEAK FLAME SPEED (M/SEC)	O/PRESS @ 6 M (MBAR)	O/PRESS PEAK (MBAR)	REF NO
METHANE	50 m^3 TUBE	YES	RING	2	5	0.3	10.0	200-400	600	-	580	11
PROPANE	"	YES	RING	2	5	0.3	5.75	250	550-800	-	600	1
METHANE (PRE-DICTION)	"	YES	RING	2	5	0.3	9.5	500	800	400	700	6
METHANE	"	YES	RING	2	5	0.3	9.5	300 (5m)	300	250	-	11
METHANE	"	YES	NONE	-	-	-	9.5	-	-	-	120	11

TABLE 2 SUMMARY OF RESULTS FOR PLANAR IGNITION

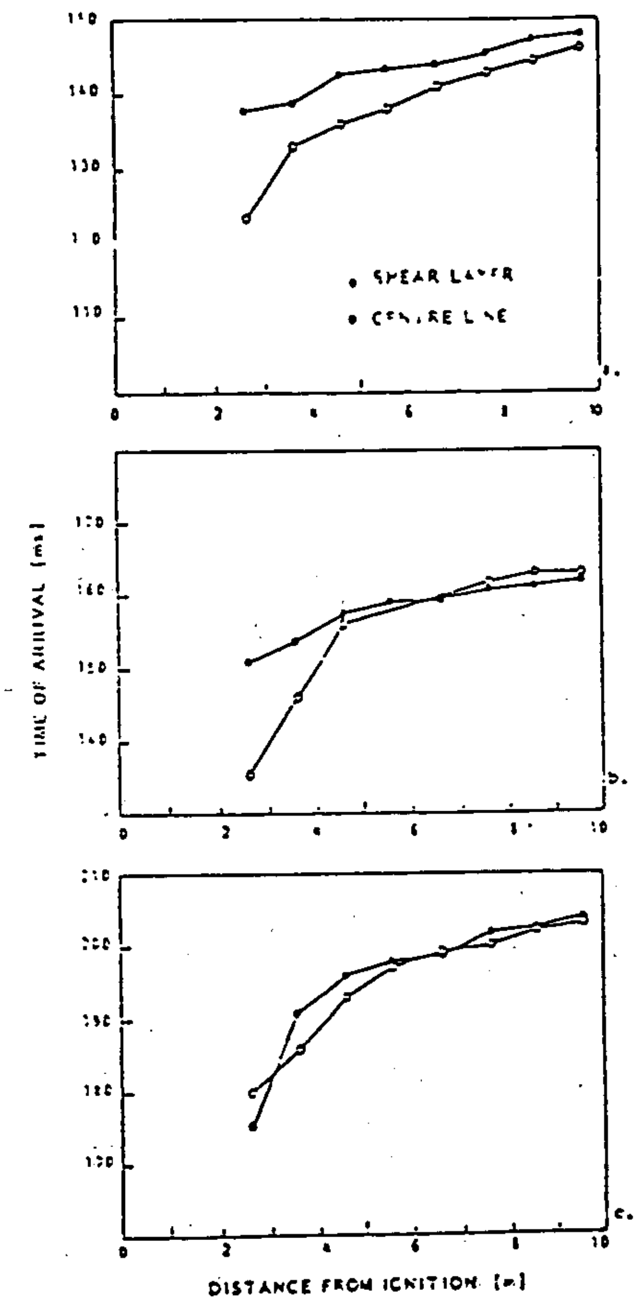
Contents

GAS	RIG	CONFINED	OBSTACLE TYPE	OBSTACLE SPACING (M)	NUMBER OBSTACLES ARRAYS	BLOCKAGE	MIXTURE % V/V IN AIR	FLAME SPEED @ 6M (M/SEC)	PEAK FLAME SPEED (M/SEC)	O/PRESS @ 6 M (MBAR)	O/PRESS PEAK (MBAR)	REF NO
NATURAL GAS *	4000 m^3 WEDGE	NO	NONE	-	-	-	10.0	-	145 (JET (VELOCITY)	-	222	13
NATURAL GAS *	"	NO	TUBE ARRAYS	4	3	0.4	9.8	-	97	-	280	12
NATURAL GAS	"	NO	"	4	3	0.4	10.4	-	170	-	710	13
PROPANE	50 m^3 TUBE	YES	NONE	-	-	-	4.5	-	-	-	3000	14

TABLE 3 SUMMARY OF RESULTS FOR JETTED IGNITION

* These results are highly dependent on the jet orifice.

Contents



Time distance plots of the flame propagation along the centerline and along the shear layers for three different tests in the same geometry; BR = 0.3 and 5 rings.

FIGURE 1 (REF [8], Fig 7)

Contents

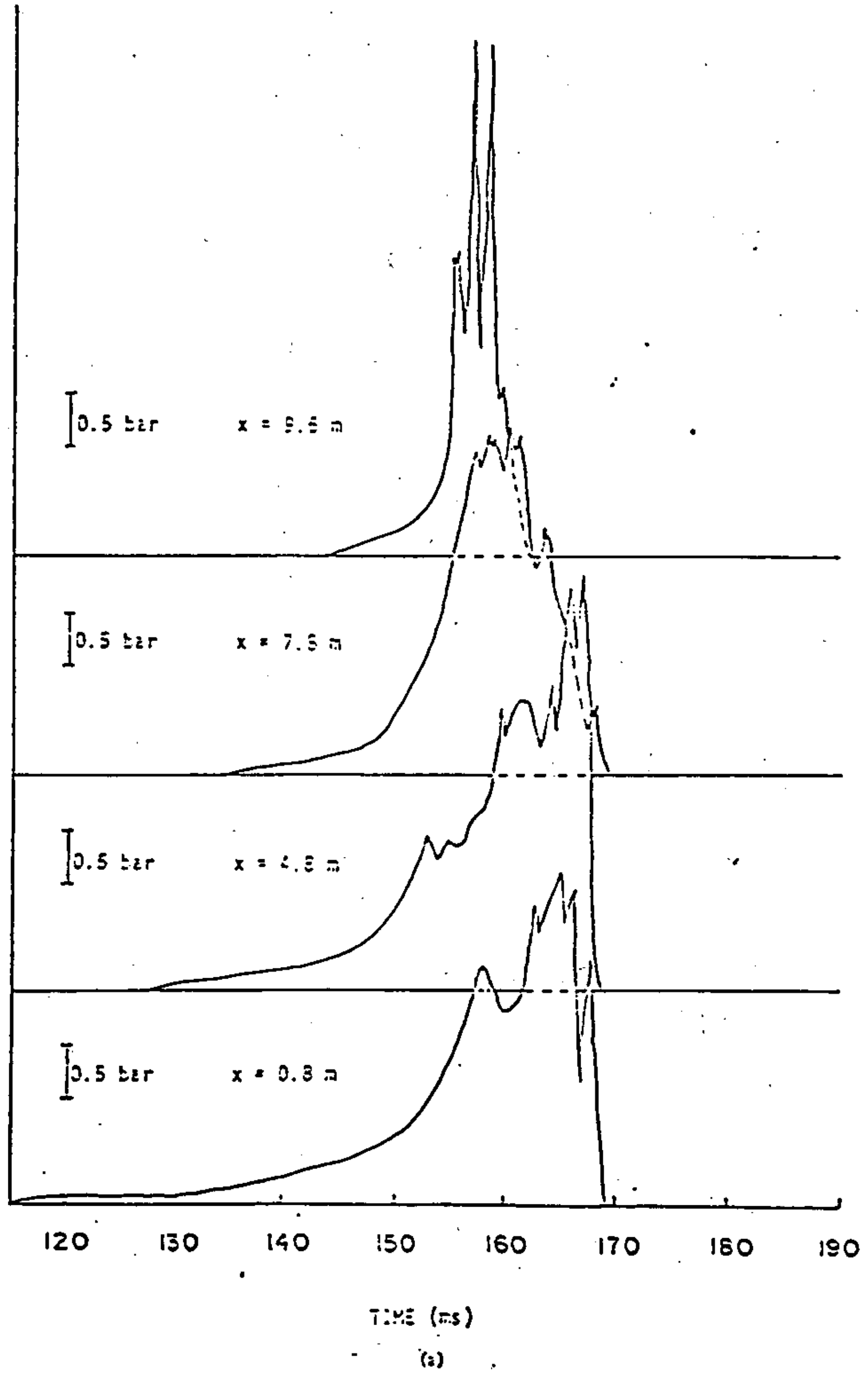
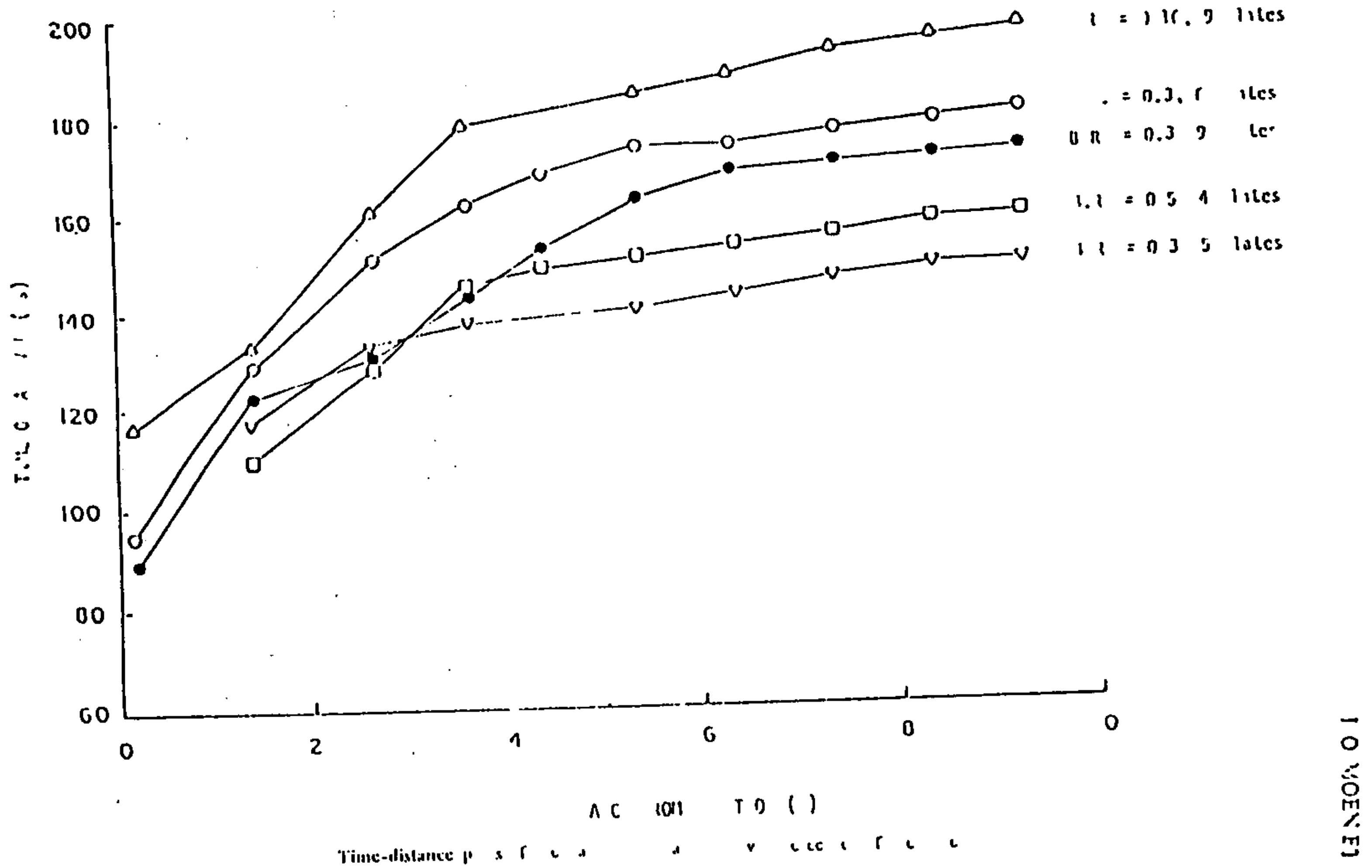


FIGURE 2 (REF [11], FIG 4(a)

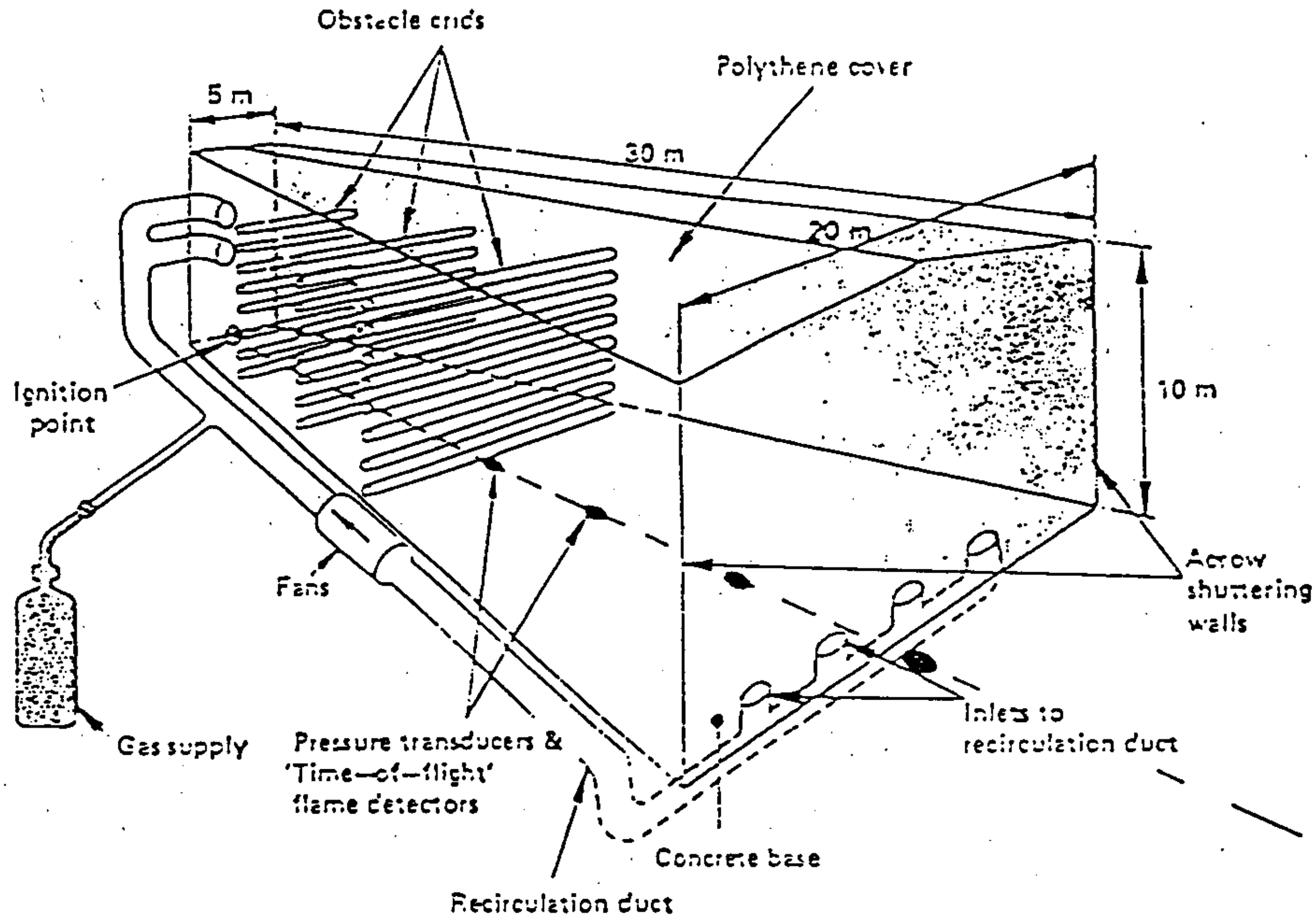
Contents



Time-distance p s f
various obstacle configura s

FIGURE 3 (REF[11], FIG 5)

Contents



Schematic diagram of experimental rig.

FIGURE 4 (REF [13], FIG 2)

Contents

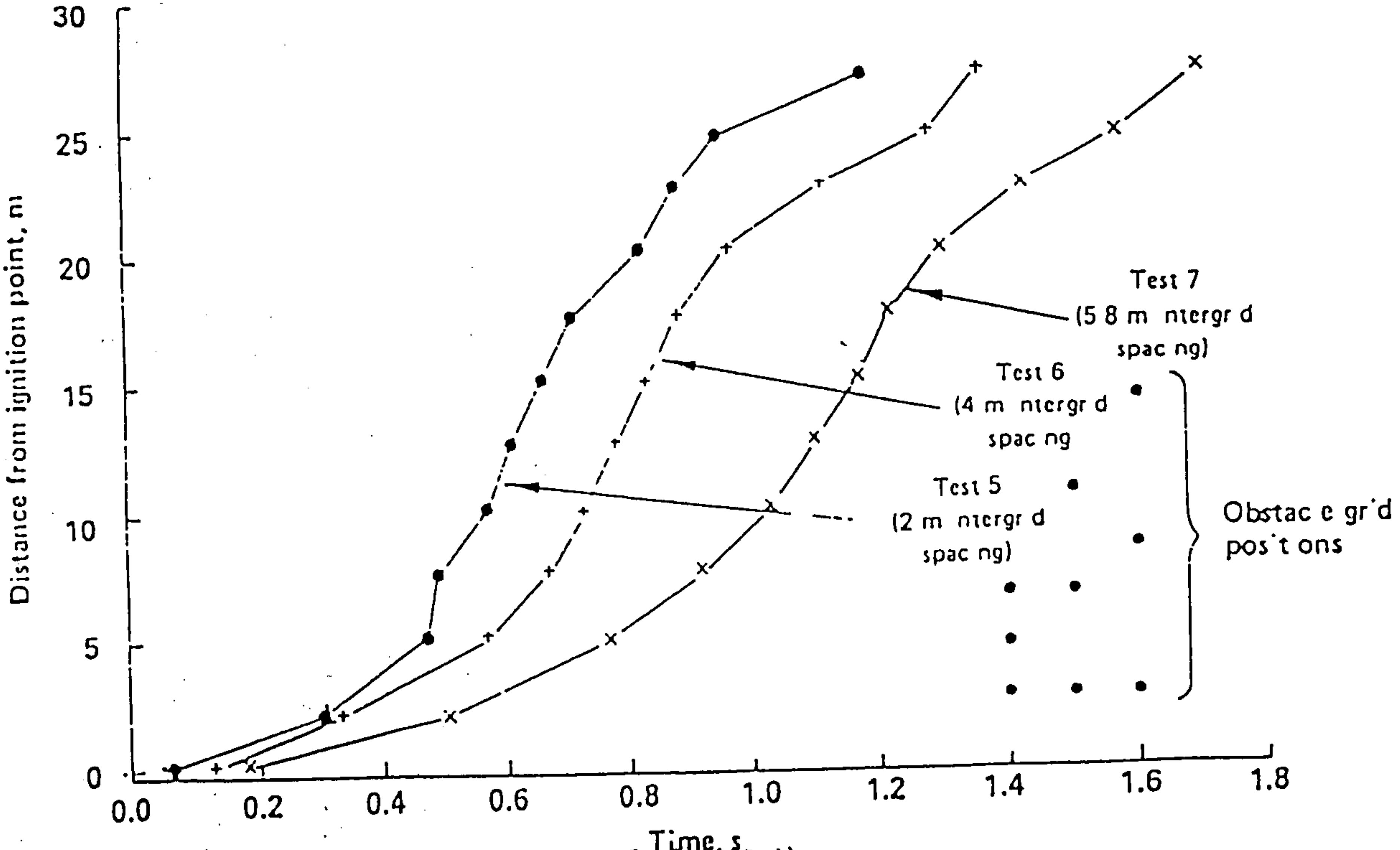


FIGURE 5 (REF [13], FIG 4)

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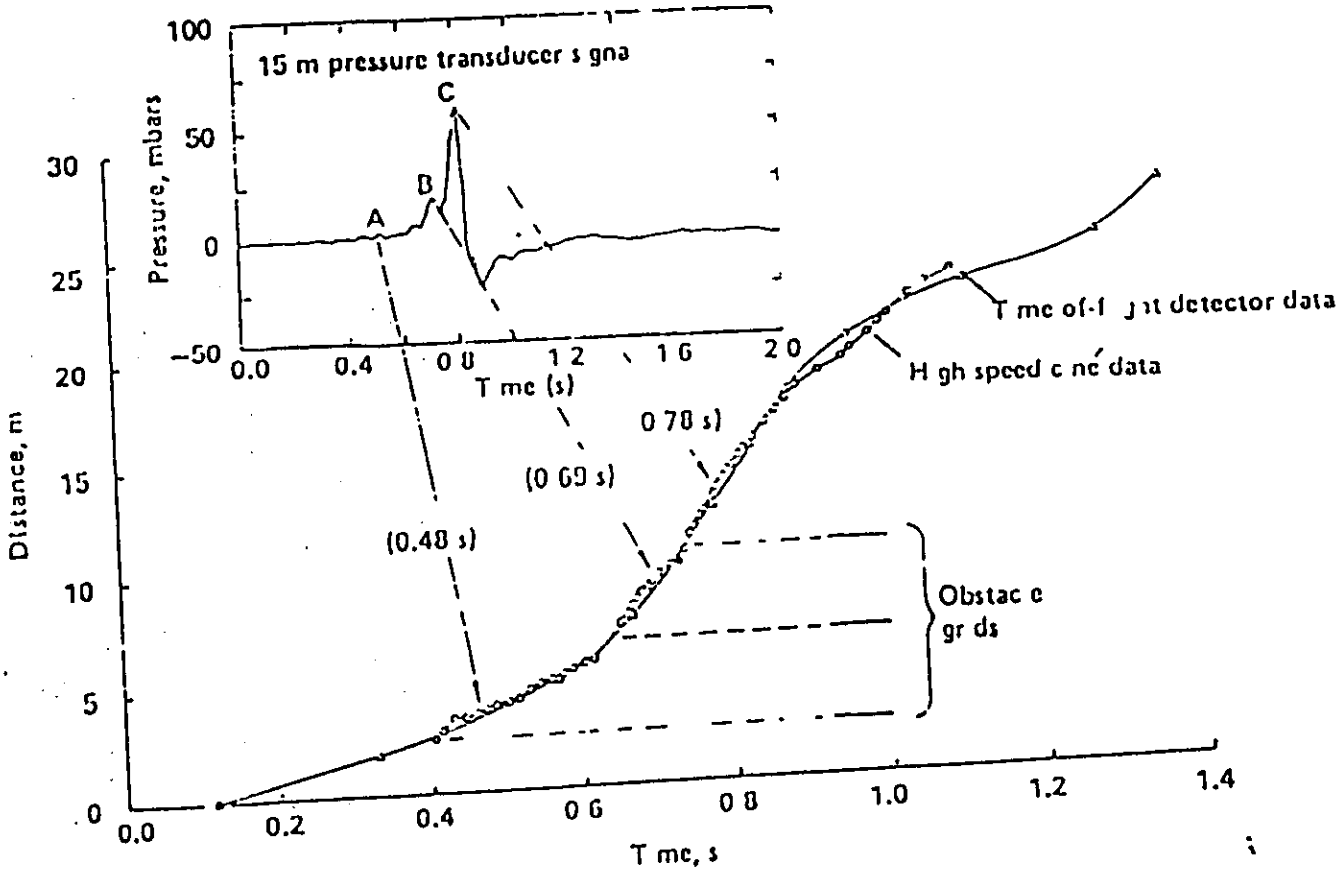


FIGURE 6 (REF [13], FIG 6)

Contents

FIGURE 7 (REF[14[, FIG 13)

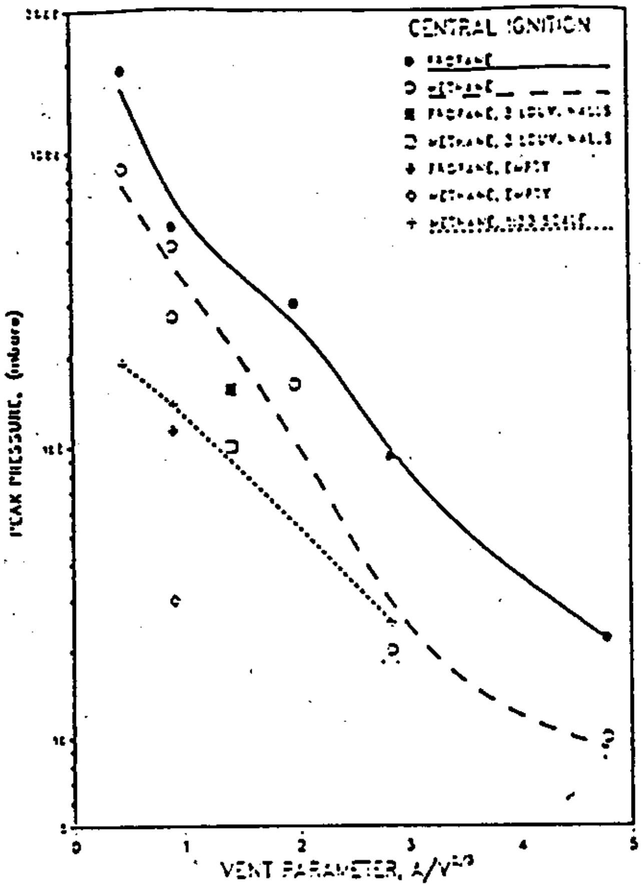
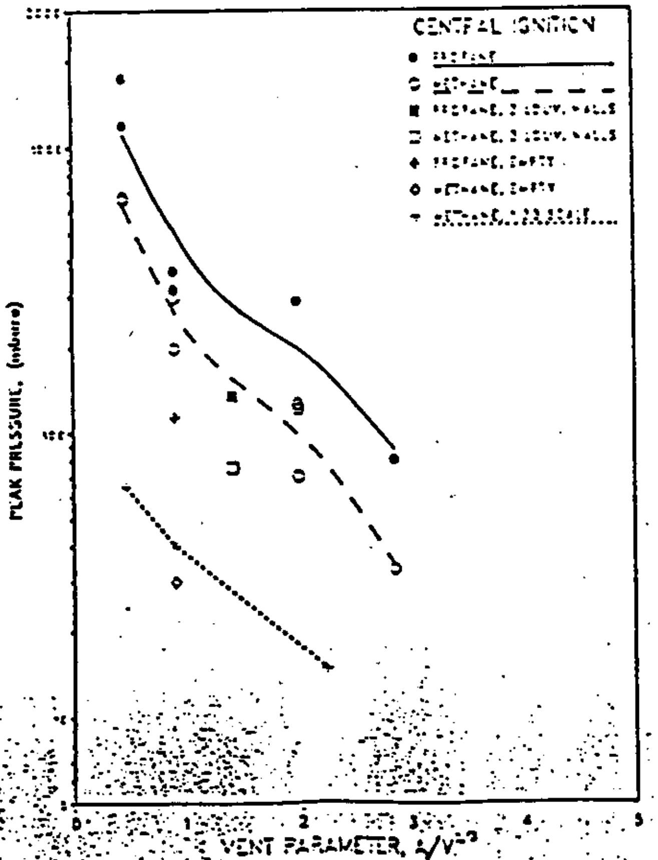
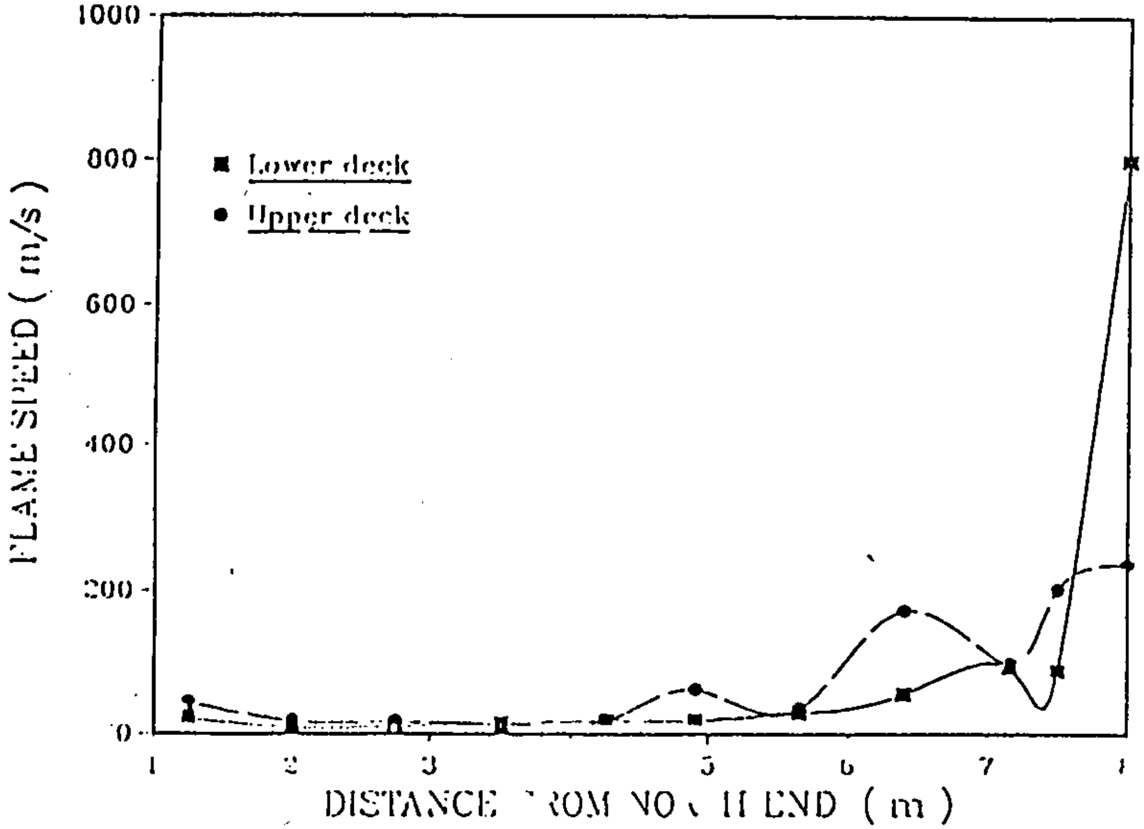


Figure 12 Peak pressure as function of vent parameter for the centrally ignited (UD) explosions in the 1:5 scale M25 separator module



[illegible] Peak pressure as function of vent parameter for the centrally ignited (UD) explosions in the 1:5 scale M24 compressor module

Contents



Flame speed versus distance along the model for the case which is ignited at the open north end

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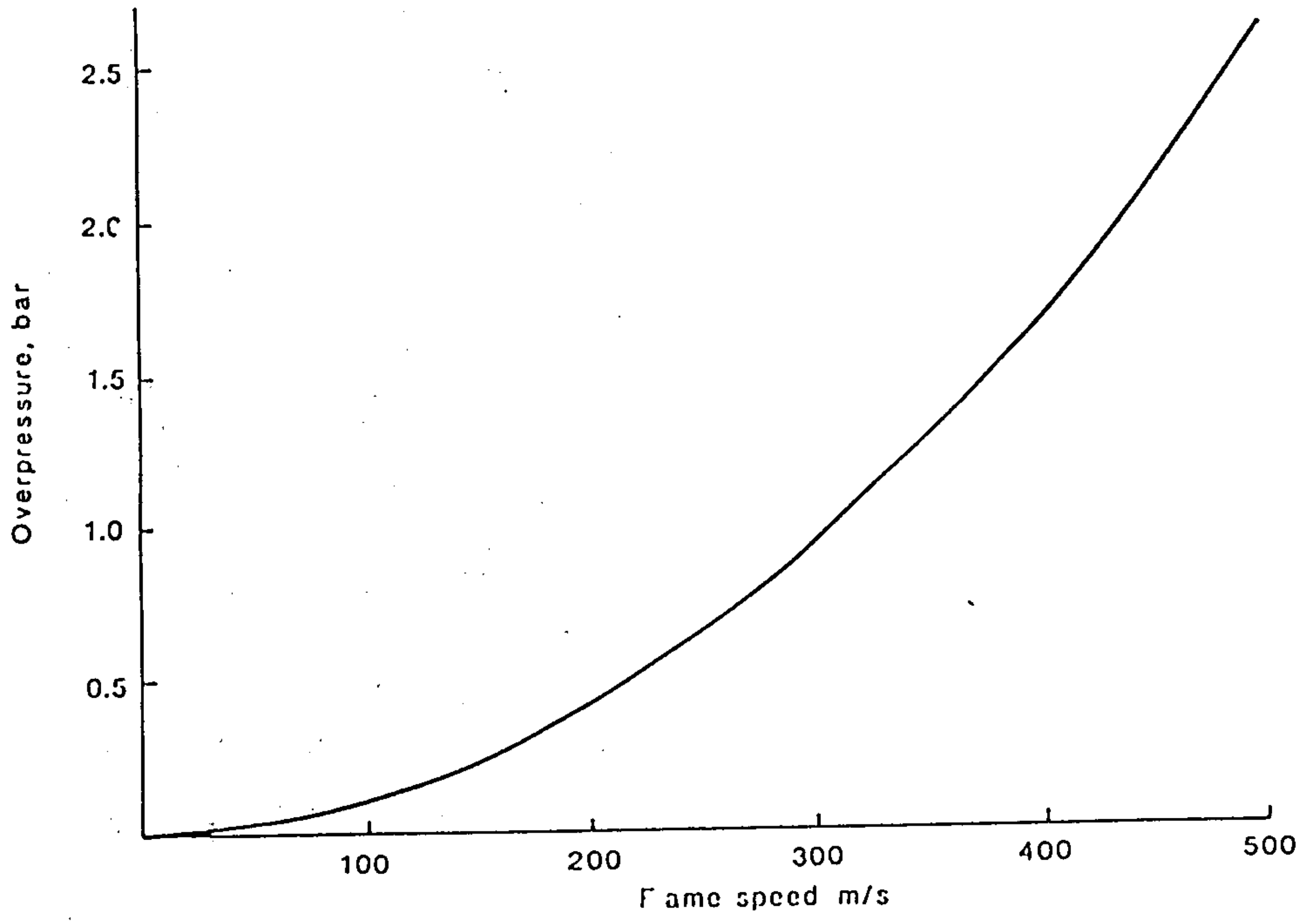
FIGURE 8 (REF]14[, FIG 17)

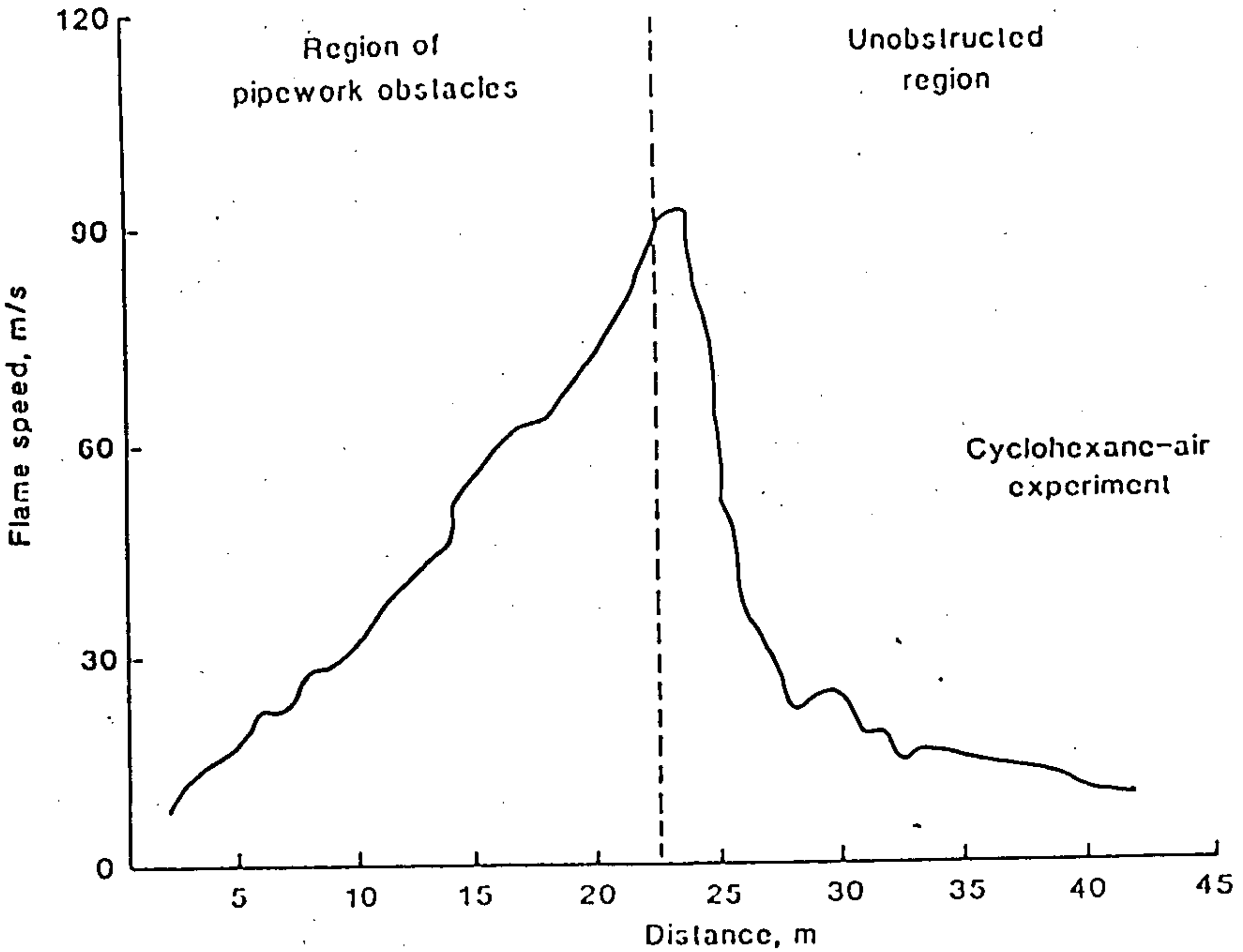
Contents



RELATIONSHIP BETWEEN FLAME SPEED AND OVERPRESSURE [11]

FIGURE 9 (REF[15], FIG 1)

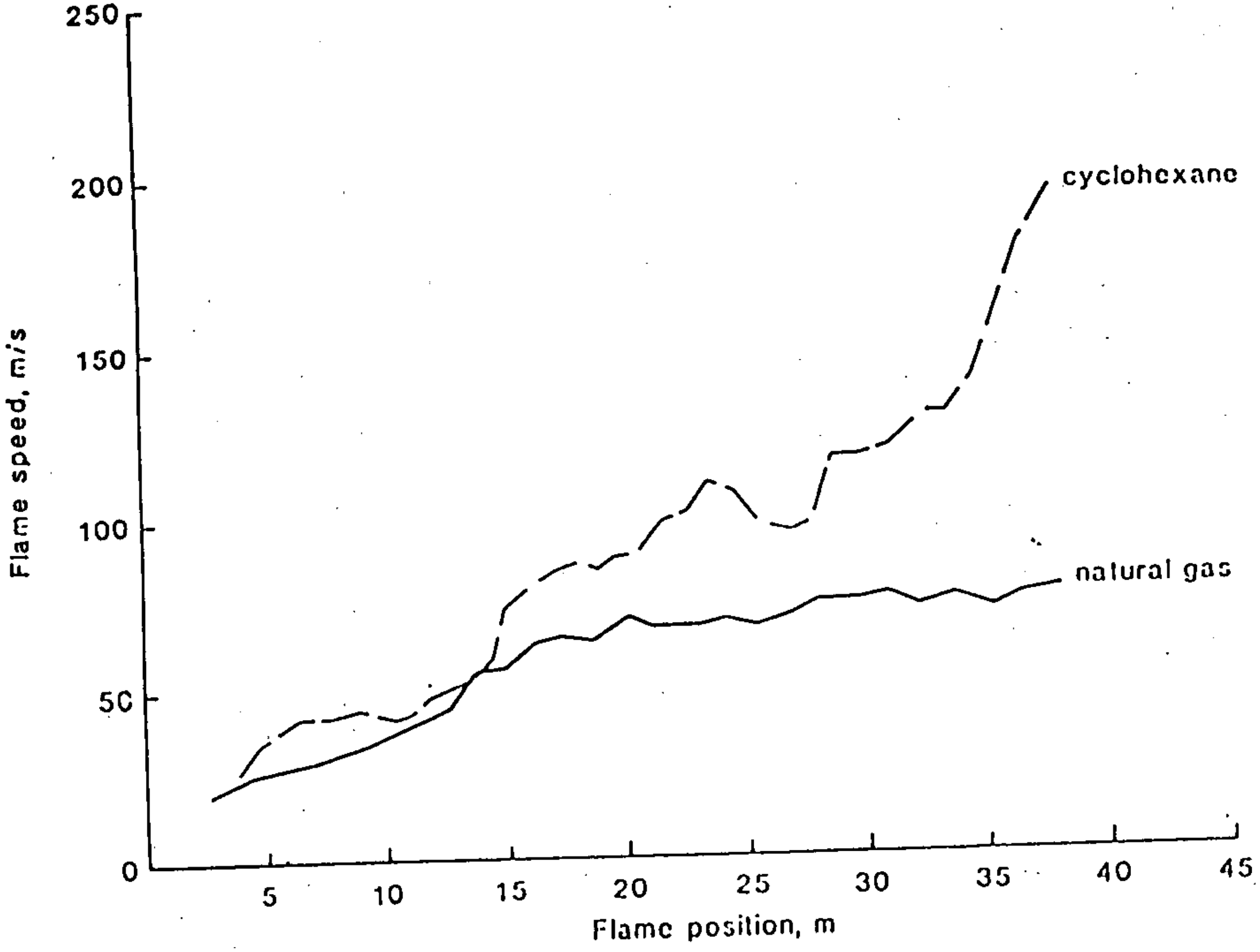
Contents



FLAME ACCELERATION IN REGION OF REPEATED OBSTACLES AND DECELERATION ON EMERGING INTO UNOBSTRUCTED REGION

FIGURE 10 (REF [15], Fig 4)

Contents



FLAME ACCELERATION IN 45m LONG REGION OF REPEATED OBSTACLES

FIGURE 11 (REF [15], FIG 5)

Contents