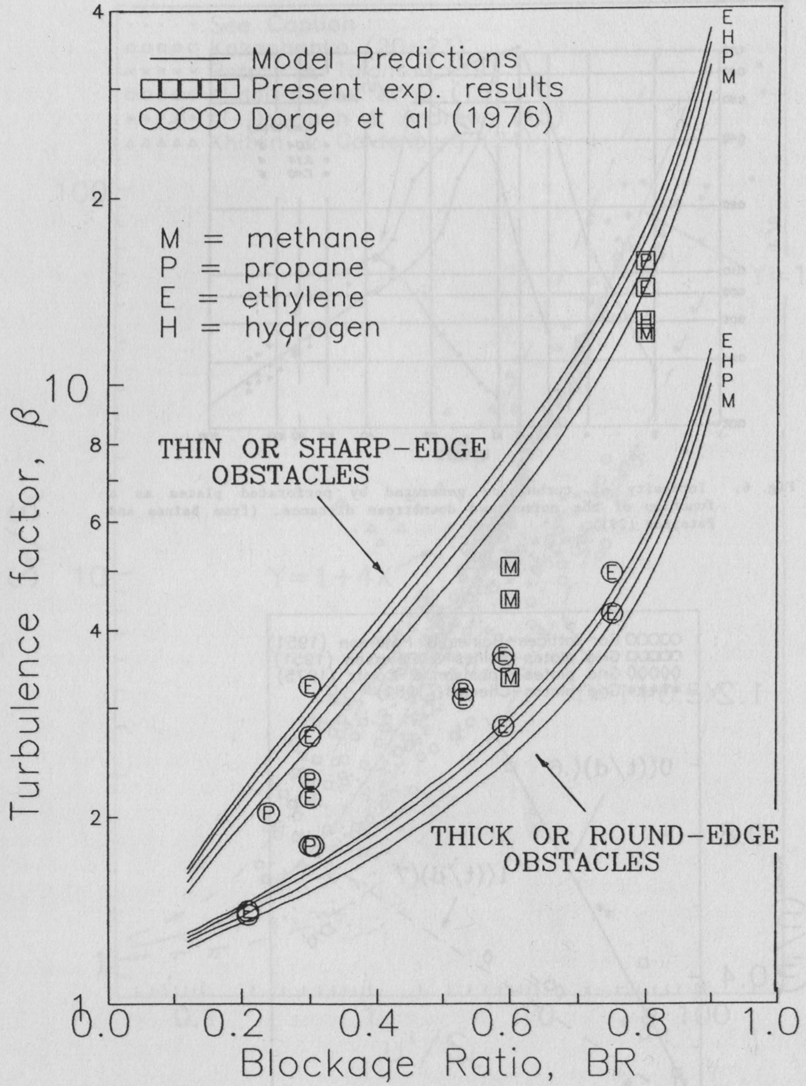

Fig. 8. Model predictions and experimental measurements of the turbulence factor induced by a single obstacle in spherical explosions as function of the obstacle blackage ratio and geometry and also as a function of the type of explosive gas/air mixture.

EXPLOSION HAZARD ASSESSMENT OF OFFSHORE MODULES USING 1/12th SCALE MODELS

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SYNOPSIS

A series of explosion experiments are described in which two 1/12th scale models of representative offshore modules were tested using ethene and propane as fuel gas. Estimates of the maximum "worst case" overpressures at full scale were obtained from the results by means of a fractal scaling theory.

In addition, the experiments yielded information on the sensitivity of explosion overpressure to ignition location, full pressure-time histories at specific locations, and an understanding of the role of particular features of the structure in the development of an explosion.

The range (and limits) of applicability, and the advantages and disadvantages, of this approach to explosion hazard assessment are discussed.

KEYWORDS
Explosions; Hazards; Offshore Modules; Models; Scaling;

1. INTRODUCTION

Explosion hazard assessment is an important element in the safe design of new offshore platforms, and must be considered in the development of an installation safety case. In addition, it is important to be able to quantify the magnitude of explosion hazards on existing installations, so that, if necessary, remedial measures can be evaluated and implemented.

Computational methods of explosion hazards assessment currently available fall into three categories (see, for example the review in [1]). Computational Fluid Dynamic (CFD) methods attempt to simulate the course of an explosion at full scale directly, requiring substantial computing resources. Empirical methods use correlations of experimental datasets to attempt to extrapolate to real cases. Between these two approaches come "Physical" models that attempt to describe the global physical processes during an explosion, with the individual sub-models calibrated against a wide range of experimental data. Thornton Research Centre is involved in developments in all three categories (and has recently published the basis of a physical model [2]).

It is likely that, ultimately, the most effective approach to explosion hazard assessment will come from computational methods. However, the models currently available have only been tested against very limited appropriate experimental data (see, for example, [3]), especially at anything approaching full scale. As a result, different models may give widely differing answers for the same geometry.

An alternative approach, adopted for the present study, is to conduct experimental explosions in (relatively) small-scale models of the specific structure being considered. The results must then be scaled up, to obtain an assessment for the real structure. At Thornton Research Centre, this is done using a fractal scaling theory developed by Taylor and Hirst [4].

It is well known that reducing the linear scale of an explosion experiment will (all other things being equal) reduces the flame speeds and overpressures. By contrast, increasing the reactivity of the flammable mixture (for example, by using a more reactive fuel gas) will increase the flame speeds and overpressures. Taylor's theory quantifies both these effects in terms of the fractal dimension of the true area of the wrinkled flame front. This fractal scaling theory has been validated in a number of experimental studies in a variety of different experimental configurations [5,6].

Of particular relevance to the present experiments (carried out on models representative of modules on an offshore natural gas platform), the theory predicts that experiments at 1/12th scale using ethene-in-air will result in roughly the same flame speeds and overpressures that would occur at full scale with methane-in-air. The theory can be directly tested by also carrying out experiments at 1/12th scale using propane-in-air. These are predicted to result in flame speeds approximately one half, and overpressures approximately one quarter, the values measured with ethene-in-air.

2. THE TEST MODELS

Two representative 1/12th scale models were constructed. Both models were made from steel with an entirely welded construction, designed to withstand internal overpressures of at least 2 bar. Primary steelwork, vessels and piping greater than 120 mm diameter were modelled to scale. Blast/fire walls (marked on Figures 1 and 2) were represented by sheets of 12 mm Lexan (polycarbonate), to permit photography of the development of the explosion inside the module.

The "process" module (Figure 1 and Plate 1) was rectangular, with dimensions 1.92 m long by 1.75 m wide by 1.44 m high (corresponding to 23 m x 21 m x 17 m at full scale), giving a volume of 4.8 m^3. There was a blast/fire wall at each end. The total vent area was approximately 4.6 m^2 (giving a vent parameter $A_v/V^{2/3} \sim 1.61$). The module contained four large vertical separator vessels along one blast/fire wall (to the right of Plate 1). The remainder of the module contained large diameter piping (up to 75 mm diameter - corresponding to 900 mm at full scale), with blockage perpendicular to the vented sides of 25% to 30%.

The "wellhead" module (Figure 2 and Plate 2) was "T" shaped, with maximum dimensions 2.00 m long by 4.37 m wide by 1.44 m high (corresponding to 24 m x 52 m x 17 m at full scale), giving an internal volume of 9.5 m^3. The total vent area was approximately 6.6 m^2 ($A_v/V^{2/3} \sim 1.63$). Each arm of the "T" contained 21 wellheads (43 mm diameter conductors, X-mas trees and associated flow lines), in a square array, giving a blockage perpendicular to the vents of approximately 35%. The wellhead conductors and X-mas trees (crudely represented as cuboids of appropriate volume) can be seen painted red in Plate 2. The central section contained extensive flowlines (10 mm diameter) and manifolds running from the wellheads to the "process" module.

The "weather" deck was solid, with grated "mezzanine" and "main" decks represented by perforated sheets (hole diameter 15 mm, for 46% open area). Modelling gratings is difficult. Simply using scaled-down gratings can result in a flame front being partly extinguished as it passes through (by the same mechanism as a flame trap). Although the use of perforated sheet with larger holes overcomes this problem, and gives the correct blockage, the development of turbulence downstream of a real grating is poorly modelled. Nevertheless, such a perforated sheet is a pessimistic representation of a real grating. Turbulence, and consequent high flame speeds, will persist further downstream (relative to the model) than at full scale.

The models were mounted upside down, for ease of access, whilst still allowing venting through the grated sections of main deck (i.e. through the roof of the models). Legs (with length scaled to the distance to the sea surface) were fixed above the wellhead model, to model the restriction of venting between the platform legs, and to make photography look more realistic. No attempt was made to model the sea surface itself. This neglects any confinement of venting gases beneath the module.

The entire model was mounted on a stand, to give a 1.1 m space underneath in which to locate the gas circulation system and other instrumentation. The tests were carried out on a 10 m x 30 m concrete pad at a test site near Buxton in Derbyshire (altitude 430 m above sea level).

3. INSTRUMENTATION AND CONTROL

The test gas was contained within the model by (2 m wide, 18 μm thick) clingfilm, held over the grated roof and open sides of the model by flexible magnetic strips. It proved impossible to fix the clingfilm in winds speeds greater than ~12 m/s. This also indicates that in the explosion, the clingfilm would be blown away at an overpressure of rather less than 5 millibars, and have no significant effect on the development of the explosion.

The test gases were CP grade (> 99.5% pure) ethene and propane. A slightly rich fuel gas concentration of 1.1 times stoichiometric was used (4.44 ± 0.10 vol.% propane, or 7.19 ± 0.10 vol.% ethene). In previous experiments, this concentration has been observed to give the maximum burning rate, and hence the greatest flame speeds and overpressures, and is therefore appropriate for a "worst case" experiment.

Fuel gas was bled into a flexible plastic duct, from where it was circulated through the test model using a fan. The gas mixture in the model was sampled at four points, and analysed using an ADC infra-red gas analyser, calibrated before each test against a certified mixture of fuel gas in nitrogen. Over a period of approximately half an hour, the fuel gas mixed uniformly throughout the model (typically varying by less than 0.1 vol.% between sampling points).

The fuel gas concentration always fell slowly over time, owing to imperfections in sealing the edges of the clingfilm sheets, and the removal of gas from the model through the sampling points. Therefore, excess fuel was initially admitted. When the required concentration had been reached (and following appropriate safety checks), the test was carried out automatically using a custom-built (Geoquip) sequencer to isolate the model, start the high speed camera, trigger the overpressure data collection system, and fire the electric spark igniter.

Pressure-time histories were obtained using ten Bruel and Kjaer "8103" hydrophones, connected (through Bruel and Kjaer "2634" charge amplifiers) to a Datalab Multitrap transient recorder sampling at 20 kHz, controlled by Datalab's "Acquire" software running on a HP 2000 series microcomputer. The locations of the hydrophones are shown in Figures 1 and 2. A number of hydrophones were mounted flush with the model floor/walls, to give wall pressures. The remaining hydrophones were the free standing "pencil" type. All hydrophones were calibrated using a Bruel and Kjaer "piston phone", which applies a known oscillating pressure to the hydrophone (approximately 5.5 millibars rms). The calculated calibration factors, and hence the final overpressure measurements, were accurate to ±1%, which is significantly better than the repeatability of the experiments.

Each test was filmed through one of the Lexan walls using a Hadlands Photonics Locam high speed camera, running at 500 frames/s (calibrated using a timer light on the front of the test model). Examination of the high speed film gave information on the development of the flame front, and was used to obtain flame speeds.

Close to one hundred experiments were carried out in total.

4. RESULTS FROM PROCESS MODULE

Three ignition locations in the process module were studied (see Figure 1). The difference between the peak overpressures measured at any hydrophone on repeat tests averaged less than 10%. Such repeatability is extremely good, compared with typical experimental scatter of 30% or more in previous explosion field experiments.

The explosion development from the three ignition positions was significantly different. Ignition at the centre of the model (ignition point 3) gave the lowest peak overpressures (see Table 1), which is consistent with the open sides resolving the greatest solid angle at this point (and with the distance between the ignition point and the centre of the vent area being the shortest). The pressures at all six hydrophones in the model rose and fell together, with very similar peak values (Figure 3). Furthermore, the timing of the overpressure peaks was very close to the time of flame emergence from the model determined from the high speed films. Thus, the pressure inside the model appears to behave quasi-statically, with the peak overpressure throughout the module determined by the peak flame speed at any point.

Comparison of pressure-time histories from tests using ethene and propane (Figure 4, in which the propane pressures have been multiplied by four and the times halved, in accordance with the predictions of the fractal scaling theory) shows remarkably good agreement. Not only does the peak overpressure scale correctly, but also the time of arrival and duration of the overpressure pulse are closely scaled. The implication is that the overpressures expected with methane at full scale are indeed close to those observed with ethene at 1/12th scale (as the fractal scaling theory predicts). Furthermore, that complete pressure-time histories for methane at full scale can confidently be predicted by taking the results with ethene at 1/12th scale and increasing the time axis by a factor of twelve.

The experiments using the other two ignition points showed considerably more variation between the peak overpressures at different hydrophone locations, accompanied by marked pressure oscillations. The maximum overpressures were somewhat higher than for central ignition, and the peaks were of somewhat shorter duration. However, despite the oscillations, the fractal scaling theory was still well obeyed (Figure 5).

The pressure oscillations were reduced by approximately 30% by covering the Lexan walls with a 1.5 cm "kaowool" (ceramic fibre) blanket. This indicates that the oscillations are caused by interaction of the flame front with acoustic waves, reflected from the blast walls, as the flame front accelerates down the model from one blast wall towards the other.

TABLE 1 - Peak overpressures in the process module

PEAK OVERPRESSURES (millibars)	IGN Pt.1 (Corner)	IGN Pt.2 (Side)	IGN Pt.3 (Central)	IGN Pt.1 (Corner) LAGGED
ETHENE	449; 487	179;152;166	136 ± 11	339; 317
PROPANE	108; 105	52; 51	31 ± 2	82; 78
RATIO (Eth/Prop)	4.39	3.22	4.35	4.10

5. RESULTS FROM WELLHEAD MODULE

5.1 Tests Using Propane

Four ignition points (see Figure 2) were tested on the wellhead module. Central ignition (point 2) showed similar behaviour to that seen for central ignition on the process module. The pressures at all the hydrophones in the module rose and fell together, with very similar peak overpressures throughout the module (compare the "central section" and "wellhead" averages in Table 2), coinciding with the time of flame emergence from the sides of the module (e.g. Figure 6).

Plate 3 shows a sequence of frames (at 2 ms intervals) from a test using propane, with ignition at point 2. Particularly noticeable is the way the flame front strongly accelerates through the two wellhead sections (the outer sections of the module), where it passes a "forest" of twenty vertical conductors. In this experiment, the flame speed just before emergence was close to 140 m/s. In the case of ignition point 1 (on the floor of the model, directly beneath ignition point 2), this acceleration was sufficient to increase the local peak overpressure (i.e. in the wellheads) by 100 millibars (see Table 2).

Tests using ignition point 3, at the outermost ("south") edge of the module, gave quite different results (e.g. Figure 7). The flame front gradually accelerated across the model. Again, the strongest flame acceleration occurred in the "forest" of wellhead conductors, just prior to flame emergence. Measurements from the high speed film gave a flame speed of 30-40 m/s as the flame front entered the central section, 60-80 m/s as it entered the wellhead opposite the ignition point, and reaching 180 m/s just before emerging from the side of the model. The maximum overpressure was also recorded in the wellhead opposite the ignition point (i.e. at hydrophone 6), and coincided with the time of flame emergence from this edge of the module. This maximum overpressure was some 20% greater than for central ignition. By contrast, the peak overpressures at all other hydrophones were much lower than for central ignition

5.2 Tests Using Ethene

A small number of tests were also carried out using ethene. Pressure-time histories at the hydrophones in the two wellhead sections from one of these tests with central ignition (point 1) are shown in Figure 8. Since these two hydrophones are symmetrically positioned, they would be expected to show similar overpressures (as was indeed the case for the tests with propane). Instead,

TABLE 2 - Peak overpressures in the wellhead module

PEAK OVERPRESSURES (millibars)	IGN Pt.1 (Central)	IGN Pt.2	IGN Pt.3 (Edge)	IGN Pt.4 (Rear)
<u>BASE DESIGN</u>				
ETHENE				
Central Section	1182 ± 177			
Wellhead Section(s)	1375 ± 120		(4709)	
PROPANE				
Central Section	275 ± 18	275 ± 26	133 ± 38	112 ± 14
Wellhead Section(s)	377 ± 21	283 ± 28	442 ± 29	118 ± 10
Max. Flame Speed (m/s)	150	140	180	
RATIO (Ethene/Propane)				
Central Section	4.3 ± 0.7			
Wellhead Section(s)	3.6 ± 0.4			
<u>SHORTENED CONDUCTORS</u>				
ETHENE				
Central Section	752 ± 187		475 ± 181	
Wellhead Section(s)	1010 ± 63		1374 ± 114	
PROPANE				
Central Section	128 ± 35		63 ± 31	59 ± 16
Wellhead Section(s)	219 ± 10		235 ± 42	70 ± 12
RATIO (Ethene/Propane)				
Central Section	5.9 ± 2.2		7.5 ± 4.7	
Wellheads Section(s)	4.6 ± 0.4		5.8 ± 1.2	
<u>AVERAGE REDUCTION</u>				
ETHENE				
Central Section	36%		43%	
Wellhead Section(s)	27%			
PROPANE				
Central Section	53%		53%	47%
Wellhead Section(s)	42%		47%	41%

the peak overpressures differ by nearly a factor of three, and this difference itself proved highly variable between tests.

The likely explanation is that when a flame front in the region of the wellhead conductors reaches some critical velocity (and associated overpressure), it accelerates extremely rapidly and unstably. This is most probably caused by strong shock-flame interactions when the flame front is already travelling at close to the speed of sound. The process is similar to the run-up to detonation.

It was not possible to obtain reliable estimates of flame speed from the high speed film for these tests, since the flame front was only observed in the wellhead section for one or two frames. This indicates an average velocity around 400 m/s.

Clearly, the fractal scaling theory, derived for turbulence-generated flame acceleration, cannot be expected to apply in this regime. Furthermore, since methane is much less susceptible to detonation than ethene, it is highly unlikely that the same phenomenon would be repeated with methane at full scale. Therefore, overpressures greater than 1500 millibars have been ignored in calculating the averages in Table 2. Surprisingly, the remaining data appears to obey the fractal scaling theory. Figure 9 shows excellent agreement in peak overpressure, time of arrival and pulse duration between a propane experiment (scaled appropriately) and an ethene result (that did not show rapid flame acceleration).

A single test with ethene using edge ignition (point 3) gave a very high maximum overpressure (close to 5 bar). This was clearly because of the rapid flame acceleration phenomenon considered above; it caused some damage to the model, and therefore was not repeated.

5.3 Tests with Shortened Wellhead Conductors

To confirm the crucial role, in this module, of the "forest" of wellhead conductors in flame acceleration, the conductors were shortened by 0.6 m (so that the X-mas trees were close to the main deck instead of being close to the mezzanine deck. The results, using both propane and ethene (see Table 2), indicate an average reduction in peak overpressure of around 40%.

Figures 10 and 11 (for central and edge ignition respectively) show that the reduction in peak overpressure is accompanied by a delay in the time of arrival and an increase in pulse duration. All three features are consistent with reduced turbulence generation leading to lower flame speeds.

6. DISCUSSION

The results described above provide a number of interesting insights into potential explosion hazards on offshore modules. First is the great sensitivity of the maximum overpressure to ignition point. Notable in this context is the fact that, for the wellhead module, the "worst case" was with ignition close to an open wall. Generally, explosion hazard assessments consider the "worst case" ignition location to be the furthest from all vent areas. In this particular case, the flame front built up sufficient speed by the time it reached the mid-point of the module to more than compensate for the fact that burnt gas could then be vented behind the flame front. The correct choice of "worst case" ignition location for assessment depends on the experience and expertise of the assessor, whatever assessment method is being used.

The second interesting insight is the fact that central ignition produces relatively uniform pressures within a confined congested region, with the peak overpressure determined by the flame speed at emergence. This suggests that relatively simple physical models (such as [2]) may be able to achieve considerable success in modelling the explosion.

Thirdly, the experiments indicated that, in some cases, high overpressures may be primarily caused by some particular feature of the geometry. Modifying this feature (in the case of the wellhead module, shortening the wellhead conductors) can have a very marked effect on the maximum overpressure.

7. THE USE OF SMALL-SCALE EXPERIMENTS IN EXPLOSION HAZARD ASSESSMENT

A small-scale experiment can be considered to be an "analogue model" of a full-scale event. On that basis, it can be compared with computational explosion assessment models. Scaled experiments have a number of advantages:

a) The geometry can be modelled in much greater detail (in the present case down to 120 mm pipework) than is currently possible with practicable CFD models, where the mesh size (and hence resolution, determined by computer run-time constraints) is typically of the order of 1 m for an offshore module.

b) In a real explosion the fluid dynamics and combustion physics processes are "modelled" correctly, whereas any numerical model can only contain simplified descriptions of physical processes.

c) Small-scale experiments can give quantitative pressure-time histories at a number of specific locations, and can offer detailed insight into the development of an explosion, making it possible to identify the critical features of a configuration that give rise to high flame speeds and overpressures. By contrast, all but the most sophisticated numerical models give only a single peak overpressure value.

d) Design modifications can be tested directly, by implementing them on the model.

The final estimates of overpressure at full scale come from scaling up the results from the small-scale experiments. Thus, the reliability of the estimates depends on the applicability of Taylor's fractal scaling theory. This was formulated for vapour cloud explosions in congested but unconfined situations, typical of onshore chemical and refinery plant. The present experiments establish the applicability of the approach to confined situations typical of offshore installations. It is important to note that experiments using several different fuels provide a direct check of the theory in the situation of interest. Thus, it is possible to use the experiments themselves to test the validity of the results.

a) The theory is most applicable where there are no severe pressure gradients within the obstacle field. It is encouraging, therefore, that for central ignition, in both modules, the pressure inside the module (behind the flame front) was extremely uniform (see Figures 3 and 6). It is notable that the agreement with the fuel-effect predictions of the scaling theory was also closest for these same ignition points.

b) The theory requires that overpressure generation is determined by turbulence-induced flame acceleration. The rapid flame accelerations (leading to close to sonic flame speeds), and consequent very high overpressures, observed in some of the ethene tests are thus beyond the range of applicability of the approach. Nevertheless, the continued agreement with scaling theory predictions at overpressures close to 1.5 bar (see e.g. Figure 9) is encouraging, since there are relatively few practical situations in which overpressures much greater than 1 bar are acceptable.

The principal disadvantages of an experimental approach are the time and cost of carrying out the experiments, and the fact that the results of an experimental programme are largely specific to the module tested. However, additional benefit can be obtained from the experiments if the results are also used to develop and validate computational explosion assessment methods such as those described in the introduction.

The objective of the present experiments was to characterise the "worst case" explosion in a module. The test models were, therefore, completely filled with an optimum fuel-air mixture, and attempts were made to identify the most severe ignition location. However, it is also an important part of risk assessment to establish how the severity of an explosion is reduced by departures from the "worst case" scenario. This would require further work to investigate the effects of changing the fuel-air mixture (the fuel concentration, the homogeneity of the mixture, and the proportion of the module volume filled), the extent of pre-existing turbulence (such as might result from a leak of fuel under high pressure), the strength of ignition (for example, a jet ignition from an initial explosion in a small confined space, rather than the low energy spark used in the present work), and a more systematic study of the effect of ignition location.

8. CONCLUSIONS

From the above discussion, it can be seen that scaled experiments have a number of distinctive advantages. They provide highly detailed and reliable information about explosion development, and pressure loadings (both by location and over time), in a specific configuration. Furthermore, the experimental approach can cope with highly complex and/or irregular geometries. In situations such as the design of new installations, where specific information is required rather than only the global peak overpressure offered by many computational methods, scaled experiments offer a cost-effective solution.

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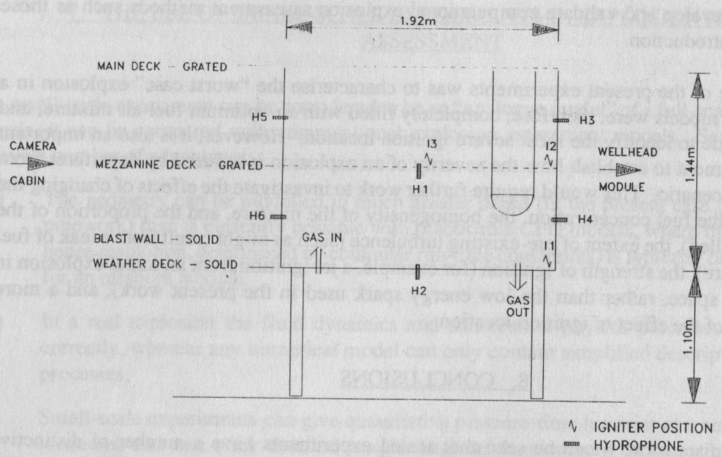

FIG. 1 - Process module (elevation) - hydrophone and ignition locations

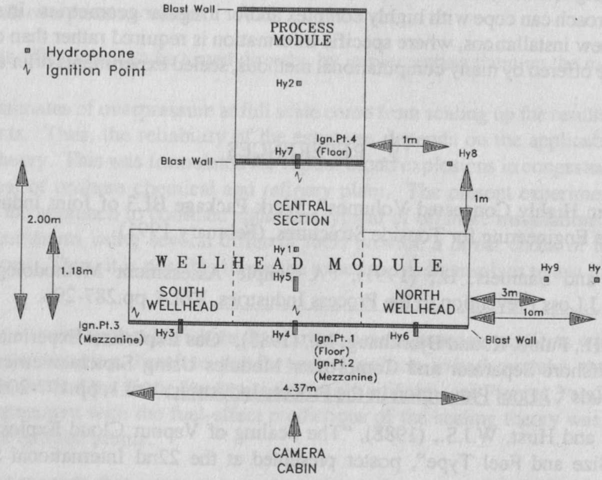

FIG. 2 - Wellhead module (plan) - hydrophone and ignition locations

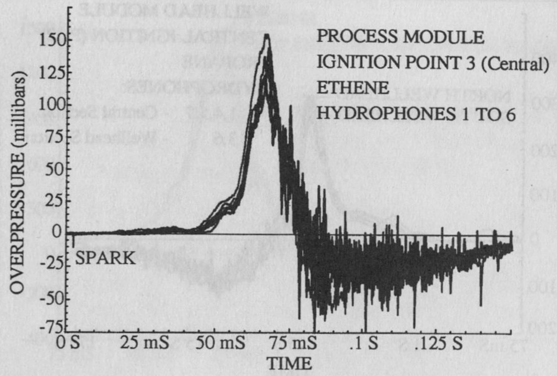

FIG. 3

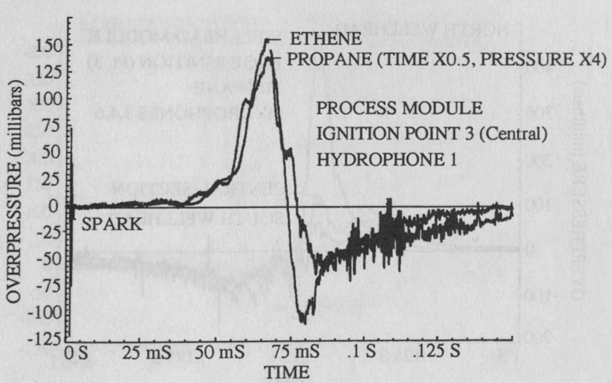

FIG. 4

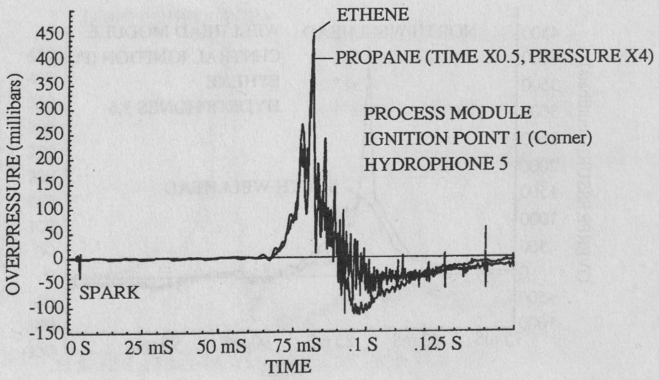

FIG. 5

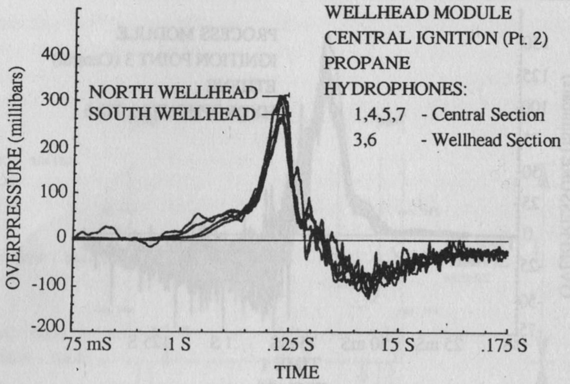

FIG. 6

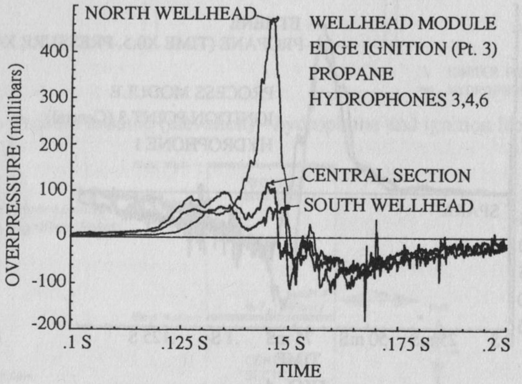

FIG. 7

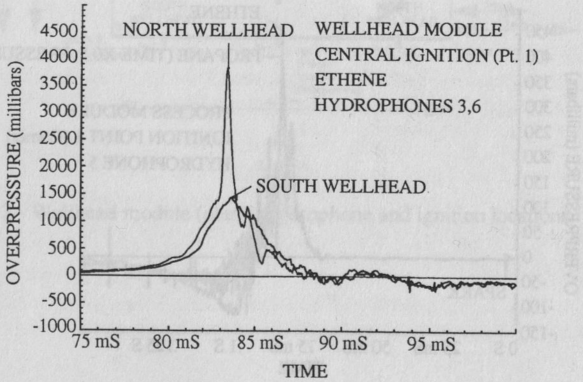

FIG. 8

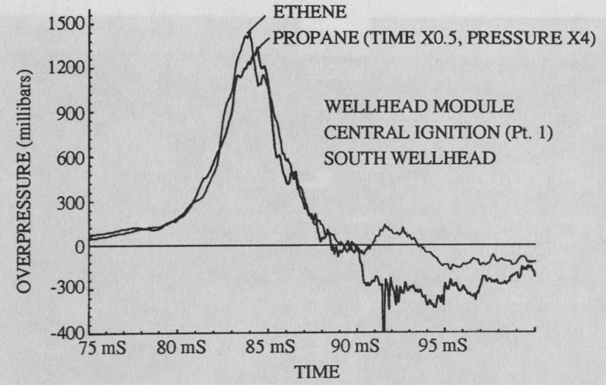

FIG. 9

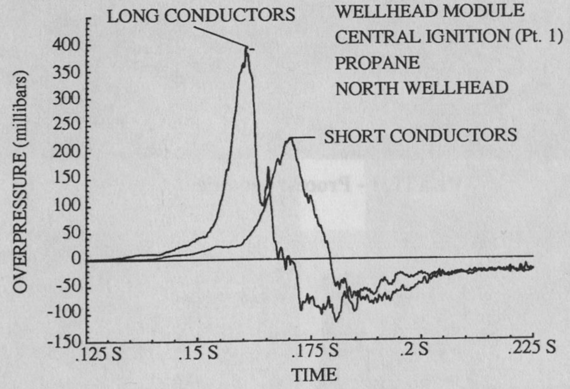

FIG. 10

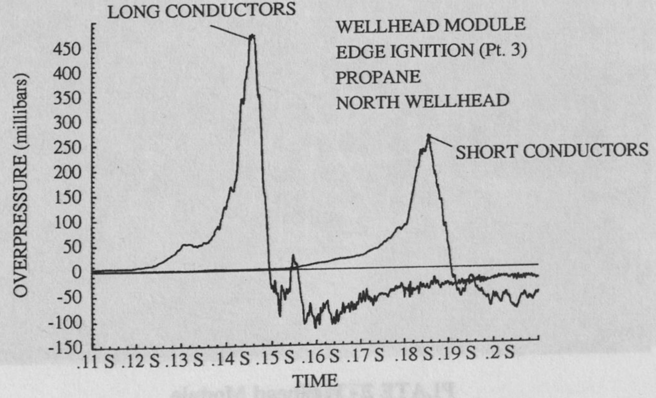

FIG. 11

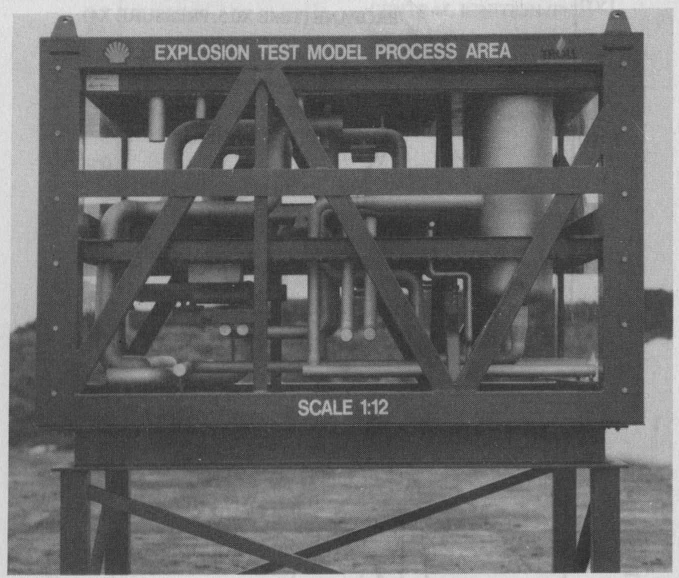

PLATE 1 - Process Module

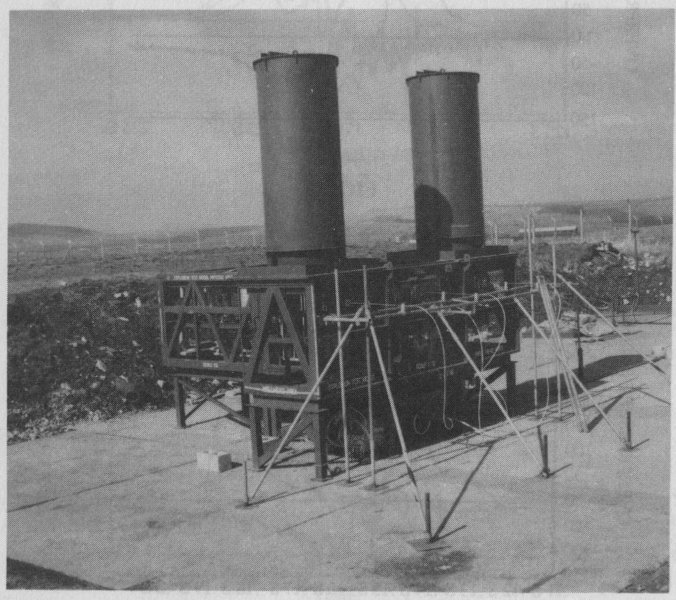

PLATE 2 - Wellhead Module

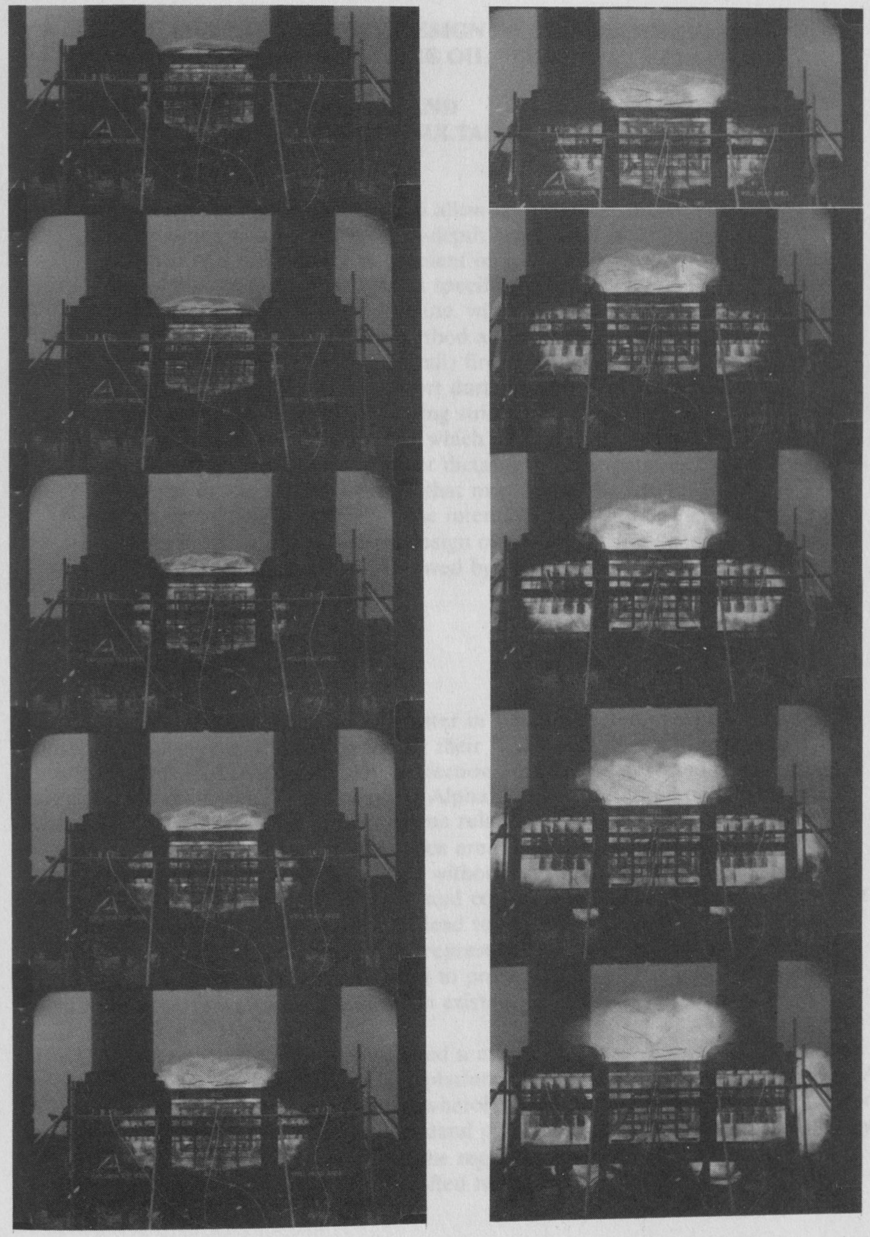

PLATE 3