Title	Blast and Fire Engineering for Topside Structures Phase 2
Publisher/Author	The Steel Construction Institute
Publication Date	1998
Scope	EXECUTIVE SUMMARY The Blast and Fire Engineering Project for Topside Structures is one of the largest research projects undertaken following the Piper Alpha disaster to address key issues relating to the characterisation and mitigation of offshore hydrocarbon explosions and fires. Phase 1 of this project started in May 1990 and was completed in November 1991 at a cost of £1,000,000. It was sponsored by 28 oil and gas companies and the UK Department of Energy and was project managed by The Steel Construction Institute. The objective was to collate, appraise and disseminate information on explosion and fire loads, the response of structures and production facilities to these loads and the options available to mitigate the loads and their effects. The deliverables from the project were: • 26 reports that summarised the state-of-the-art on explosion and fire engineering. • The `Interim Guidance Notes for the Design and Protection of Topside Structures Against Explosion and Fire' (IGN). • A proposal for Phase 2 of this Joint Industry Project based on the highest priority areas of uncertainty identified in Phase 1. Phase 2 of the project commenced in January 1994 and was completed in January 1998. It was sponsored by 10 oil and gas companies (operating in both the UK and Norwegian Continental Shelves) and the UK Health and Safety Executive. The project cost was £4,400,000. The first objective of Phase 2 was to provide specific information about the characteristics of hydrocarbon explosions and fires and means of mitigating these hazards. The second objective was to generate accurate information and data for use in evaluating and improving the accuracy of fire and explosion models. The experiments in Phase 2 were carried out at large scale to generate that is representative of offshore scenarios and to study the influence of scale on explosion and fire characteristics; all previous research in this field had been carried out at small and medium scale. The project included the following work packages: • Unconfined jet fire test programme • Confined jet and pool fire test programme • Explosion test programme • Fire model evaluation exercise • Explosion model evaluation exercise In addition, the project had an information exchange agreement with Christian Michelsen Research (CMR) in Norway. This enabled experimental data and project information to be exchanged between this project and CMR's Gas Safety Programme (GSP93-96).

Apart from the technical information obtained and disseminated in this report, everyone involved in this project has learnt many other valuable lessons. These include how to get the most for available funds, how to plan experimental programmes and how to manage the release of results.

The expense of large scale testing and practical limitations of available funding required careful consideration and prioritisation of the areas of uncertainty identified at the end of Phase 1. This prioritisation was done in consultation with industry.

A contributor to the overall success of the test programmes in Phase 2 was that a flexible plan was designed at the beginning of the project and adhered to in order not to lose sight of the overall objectives.

The Phase 2 participation contract contained a 12 month confidentiality clause. It was a unanimous decision of the project Participants to forego this clause and make the results available as soon as possible after the completion of the project. This was in recognition of the great value of the Phase 2 data to the industry and the wish to see it made available for industry initiatives on updating guidance.

The results of this project (and others which have been carried out simultaneously in the field of explosion and fire engineering for offshore structures) have implications to design guidance and the way in which new offshore facilities will be designed in future. In particular, the IGN which have been widely used since their publication in 1992 must be updated to reflect the results of all relevant research. The work to update the IGN will commence in April 1998.

This summary report presents the findings from Phase 2 of the Blast and Fire Engineering Project for Topside Structures. The report is in three parts; Part I gives an over view of the project and summarises the experimental test results. Parts II and III contain the fire and explosion model evaluation reports respectively.

Unconfined jet fire test programme

Large scale horizontal jet fire experiments were carried out by BG plc at a test site in Spadeadam, Cumbria, U.K. The aim was to study free jet fires of stabilised light crude oil and mixtures of stabilised light crude oil and natural gas. The tests also studied similar fires impinging on a cylindrical pipe target.

Twelve horizontal jet fire tests were undertaken involving releases at 5kg/s of light crude oil and gas:oil mixtures in the ratio 1:4 and 2:3 by mass. Six tests were free flames released at an absolute pressure of either 20 bar or 7 bar, and six tests (all at 20 bar) involved impingement onto a 0.9m diameter cylindrical pipe target at distances of 9m and 15m from the release point. Measurements were taken of the external flame characteristics (including flame geometry, external thermal radiation field, flame surface emissive power (SEP) and infra-red emission spectrum) in addition to measurements of the fuel flow conditions and meteorological conditions. During the impingement tests, measurements were also taken of the total and radiative heat fluxes incident on instruments maintained at 60ºC.

The key lessons learnt from these tests were:

- The crude oil only free flame releases were not able to sustain a stable flame, and therefore a small natural gas pilot flame was required to stabilise the flames in all of these tests. For one of the mixed fuel releases, the initial flame (produced by the natural gas component - 1 kg/s released at an absolute pressure of 20 bar) was also unstable, and was therefore stabilised using a small propane pilot flame.

- All tests were luminous and generated quantities of thick black smoke, mainly towards the tail of the flame. The crude oil only tests produced large quantities of smoke. The mixed fuel impingement tests produced more smoke from that part of the flame downstream of the pipe target than the equivalent free flame tests.

- Smoke prevented accurate measurement of the flame lengths. However, it was estimated that the flames were all of a similar length, extending between 25 m and 30 m horizontally in the direction of the release.

- The flames generated in all of the tests were highly radiative, and the maximum time-averaged values of flame surface emissive power (SEP) ranged from 200 to 400kW/m2. The tests at absolute release pressures of 7 bar tended to produce lower maximum SEP values than the releases at 20 bar. The maximum SEP increased with increasing gas concentrations over the range of concentrations studied.

- The total incident heat fluxes measured by instruments on the pipe target were significantly higher for the mixed fuel tests than for the crude oil only tests. The values measured for the two gas concentrations were similar on the front face of the target, but higher on the back face for tests involving the higher gas concentration.

- There was little difference between the total heat fluxes measured by instruments on the front face of the pipe target for similar releases at the two impingement distances of 9m and 15m. However, higher total heat fluxes were measured on the back face of the pipe target for all fuel types for the 9m impingement distance than for the 15m distance, consistent with the finding that the convective heat fluxes on the back face were negligible for the 15m cases.

Confined jet and pool fire test programme

Twenty-two large scale pool and jet fire experiments were carried out by SINTEF Energy Norwegian Fire Research Laboratory (NBL). These included 15 jet fires (4 horizontal jets and 11 vertical jets) and 7 pool fires, in two insulated compartments, 135m3 and 415m3. A range of parameters were varied including ventilation opening size and location, fuel type, substrate, release height and pressure. Four vent sizes were investigated which included the effect of splitting the vent area. In all except one test with gaseous propane, the fuel was a Statoil Sleipner condensate. In some of the tests cylindrical targets were introduced inside the test rig.

Gas temperatures, steel temperatures (of walls, ceilings and targets), heat fluxes (to walls, ceilings and targets), gas compositions and concentrations and fuel release rates were measured. In eleven of the tests the effect of water deluge was investigated.

The test results have been analysed and compared with results from a previous test series in the 135 m3 compartment and with knowledge summarised in Phase 1 of this project. The following conclusions can be drawn from the test results

Effect of confinement on the behaviour of jet and pool fires

- During the initial stages of fire development confined jet fires and pool fires behaved as they would in the open.

- After a short period, ranging from a few seconds to a few minutes, the development of the fire depended on the degree of ventilation control,

	specifically on the value of global stoichiometry. (Definition: global stoichiometry or equivalence ratio Φ = Air/fuel mass rate into the compartment divided by the air mass requirement for stoichiometric combustion). • For jet fires, the tests showed poor correlation between Φ and the ceiling and vent temperatures. Weak correlation was found between Φ and the wall temperature. No correlation existed between Φ and the heat flux to the ceiling whereas strong correlation was found between Φ and the heat flux to the walls. All these observations are based on vertical jet fire tests. • For pool fires, the tests showed no significant correlation between Φ and the temperature and heat flux in the compartment. However, heat flux values were significantly higher for fuel controlled fires. • A well defined horizontal interface formed between an upper hot gas/smoke layer and lower cool air layer. Depending on the relation of the vent flow and the size and position of the fire source, the conditions for ventilation or fuel controlled burning were established. When the burning approached ventilation controlled conditions, it was possible for combustion at the interface between these layers to be highly oscillatory and unstable. This led to rapid vigorous combustion, high heat fluxes and temperatures above 1350ºC due to soot oxidation (which occurs at temperatures in excess of approximately 1200ºC). • Before steady state conditions were achieved, incident heat fluxes and temperature rise rates diminished if the, fire entered a ventilation controlled regime. Copious amounts of soot were produced from incomplete combustion, particularly when the temperature of the smoke layer was > 900ºC. If the soot was deposited in areas where the temperature was below 900ºC, it acted as a heat shield insulating the surface of the walls, roof and objects from the radiative flames. • If the soot was deposited in areas where temperature was high (around 1200ºC) soot oxidation occurred thereby increasing the heat load to the walls, roof and objects. The severity of this effect and the exact temperature at which it occurred can only be estimated. Based on the experimental conditions in this project it was estimated that a localised region of high fire intensity of diameter in the region of 4-6 m was needed to ensure extensive soot oxidation, leading to the increased heat load. The resulting heat fluxes were in the order of 350-400 kW/m2 with gas temperatures above 1370ºC. • Small differences of geometry, like obstructions to a jet release, or minor changes in transients in fire development may introduce the combination of soot oxidation and 'radiation trapping' thereby stepping up the fire severity. This occurred in only one out of three ventilation controlled tests with horizontal jet releases, intended to be similar. • It seemed easier to obtain higher heat flux values and temperatures to the roof and wall surfaces near the corners than elsewhere on the surface. An example of this effect was reflected in the damage after Test 9, where the steel plates at the bottom of the west wall were totally damaged and to some extent melted. However, the exact conditions of Test 9 were not known and could not be reproduced by other tests with nominally similar conditions (Tests 12 and 14). • For the small scale fires (135m3) the CO level seemed to be more constant

when Φ varied. In the tests with temperatures above 1200ºC in the 415m3 test rig, the concentration of CO was also significantly higher than in other tests. This indicated more extensive soot oxidation resulting in more CO under these conditions.

- In the pool fire tests, the overall burning rate of condensate pool fires entered a self-limiting regime as ventilation controlled conditions were approached such that Φ was always greater than ~0.8. The final burning rate for ventilation controlled fires was lower than expected when comparing with the burning rate of an open pool fire of the same size.
- In ventilation controlled fires, soot ignition on exiting the vent can produce high levels of external radiation.
- The general trends observed in these tests are expected to be applicable to uninsulated compartments. However, the surface and gas temperatures will be lower for uninsulated compartments of similar size. When enclosures are large, the influence of thermal properties of walls and ceiling (for instance insulation) on fire development is reduced.
- In the test condition with the vent opening in one wall, the region of maximum combustion intensity shifted from the jet or pool towards the vent as Φ decreased.
- The results showed that there was no difference in the burning rate between a pool fire on a layer of shallow water and a pool fire on a steel substrate.
- The radiation from the external flames seemed to be shielded by soot in all the condensate fires. For the propane fire, Test 6, the radiation from the external flames to the surroundings was 10 times higher than the condensate fires due to less soot shielding.

Thermal load onto process vessels, pipework, module walls and decks

- The general finding in the tests was that the total incident heat flux density onto a target was up to 200 kW/m2. For certain conditions considerably higher fluxes were observed (in the order of 350-400 kW/m2). These fluxes occurred simultaneously with high temperatures throughout the compartment. The temperatures were above the saturation level of the data logging system (1370ºC).
- At steady state conditions, incident heat fluxes to the surrounding walls, ceiling and impinged objects were comparable in magnitude to those found for impinging jet fires or pool fires in the open, but can be higher under certain conditions.

Effectiveness of active water deluge mitigation systems

- During the deluge experiments the well ventilated jet fires were not extinguished by typical offshore water deluge. The jet fires continued to burn at the same rate but there was a substantial reduction in fire intensity. However, well ventilated propane gas jet fires have been extinguished during smaller scale experiments conducted prior to Phase 2.
- Fuel controlled (under-ventilated) jet fires were controlled but were not extinguished when deluge was activated soon after ignition.
- Fuel controlled (under-ventilated) jet fires were extinguished when deluge was activated 10 to 12 minutes after ignition and the fire compartment was

‘hot’

- There were no significant differences between the effects of water deluge on vertical and horizontal jet releases, for the test conditions studied.
- It is possible for the fire to re-ignite after the water deluge is terminated due to the presence of hot gases or surfaces coming into contact with fuel.
- Extinguished jet fires represent a potential explosion hazard if the fuel continues to be released.
- Generally, confined pool fires are not extinguished by water deluge, but the fire is controlled and burns at a much reduced rate.

Explosion test programme

This comprised a programme of large scale explosion experiments carried out by BG plc at a test site in Spadeadam, Cumbria, U.K. The work included the design, construction and operation of the test rig, as well as the performance of the tests. Scientific measurements were made by BG plc, in collaboration with TNO Prins Maurits Laboratory (TNO) and AEA Technology (AEA).

The explosion test rig was an all steel construction extending up to 28m long, 12m wide and 8m high giving a closer representation at large scale to an offshore module than previous tests. Within the rig, large and small steel equipment items were positioned to simulate typical process plant and pipework which would be found on an offshore installation.

The test programme comprised of a total of 27 experiments, 7 of which were additional to the original programme and were financed by the Health and Safety Executive (HSE). The first six experiments were conducted with the test rig 25.6m long, 8m wide and 8m high and with only equipment representative of the larger items of equipment that might be found on an offshore platform, so called `low equipment density' tests. A further 17 tests were carried out with additional equipment installed to provide more realistic representation of a module on an offshore platform (‘high equipment density’ configuration). The test rig was then lengthened to 28m and widened to 12m and 4 further experiments were performed.

In addition to changing the equipment density and the size of the test rig, parameter changes included different wall perimeter confinement, the use of two types of water deluge system, fuel concentration and ignition location.

Data collected included internal overpressures, external overpressures, flame arrival times, prevailing weather conditions and visual records. In some experiments, information on the net reaction load on equipment within the test rig and the response of structures outside the test rig to an explosion loading was obtained. During one test a study of the response of a selection of special wall panels and various items of safety critical equipment was undertaken, as well as the potential for missile generation.

The experiments provide an important source of large scale data against which models used for the prediction of explosion hazards in offshore installations can be validated. The results also provide important qualitative information, such as on the effectiveness of water deluge in mitigating explosion overpressures, which can be applied directly to offshore situations. The following lessons can be drawn from the test results.

Effect of equipment density

- The fine detail which was added to change from the low to high equipment density (and which increased the blockage ratio from 7.28 to 9.58 %) significantly increased the overpressures generated. It is important that such detail should be represented in any explosion assessment related to an offshore platform.

- The factor by which overpressures increased when the equipment density changed was significantly greater for end ignition cases than for central ignition. This is because the finer detail added for the high equipment density configuration increased the potential for flame acceleration.

Effect of boundary confinement

- In general the peak overpressures reduced as the degree of confinement reduced. However there were exceptions to this general trend. The most notable of these occurred in an experiment with ignition at an open end of the test rig and the flame propagating towards the opposite open end of the rig. The sides of the test rig along the path between the two open ends were closed except for a relatively small vent located in the middle of one of the sides. This vent had the effect of increasing the overpressures generated locally at the far end of the test rig. However, it is important to differentiate between local and global effects as the overpressures were otherwise reduced throughout the rest of the test rig.
- Reducing the degree of, confinement did not significantly reduce the external overpressures measured at the end of the test rig.
- Polythene sheeting was used at boundary openings to contain the flammable mixture within the test rig during gas filling. Previous work at medium scale had shown that the polythene led to a slight increase in initial flame speeds in tests where the ignition point was close to the polythene. For this reason, in the end ignition experiments, the polythene was cut using a low energy explosive chord just before ignition. The polythene has no influence when the ignition point was near the centre of the rig and in these tests it was not cut prior to ignition.

Effect of water deluge

- Two nozzle types were used during the water deluge experiments; Wormald MV57/140 nozzles (proprietary nozzles typical of those employed for fire deluge on offshore installations), and Large Droplet Nozzles (LDN) developed by BG for previous experimental work. The deluge rates for these two nozzle types were chosen such that they would, as closely as could be calculated, generate the same water volume fraction (i.e. the same quantity of water in a given volume) in the test rig. Because the droplets of the LDN nozzles are larger than those of the MV57 nozzles (and therefore fall faster) this resulted in different deluge rates for the two water spray systems (approximately 17 litres min-1 m-2 for the MV57 nozzles and 35 litres min-1 m-2 for the LDN's averaged over the floor area of the test rig).
- In every deluge experiment, the peak internal overpressures generated were less than those generated in the equivalent non-deluge experiment. The overpressure durations were greater in the deluged tests.
- In deluge experiments using the LDN nozzles, the overpressures generated were less than those generated in the equivalent deluge test with MV57 nozzles.
- These results confirm earlier work (carried out at small and medium scale)

of how water deluge influences gas explosions. For water deluge to be effective, relatively high gas velocities are required in order to break up the water droplets in the water spray. These smaller droplets, with their much higher overall surface area, are able to extract energy from and inhibit combustion in the explosion flame.

- The factor by which overpressures were reduced was greater in the end ignition experiments than in equivalent central ignition tests. Most notable, the use of deluge prevented the runaway flame acceleration which occurred in a non-deluged end ignition experiment. In the absence of deluge, this experiment generated peak overpressures of over 4 bar, whereas with deluge, the peak overpressures were 481 mbar (LDN) and 806 mbar (MV57).
- The magnitude of the external overpressures was reduced considerably in deluge tests compared to equivalent non-deluged tests. The duration of the external overpressures in the deluged tests was, however, greater than those in the equivalent non-deluged tests.

Effect of fuel concentration

- Lower overpressures (~ 50% reduction) were generated by mixtures at concentrations 25% above stoichiometric or 25% below stoichiometric concentration compared to equivalent explosions involving near stoichiometric mixtures. The overpressures generated in the lean experiment were, however, higher than had been expected from previous smaller scale experimental work.

Effect of ignition point location

- In non-deluge experiments in the 8m wide rig, the peak overpressures generated in many of the central and end ignition tests were similar. However in two instances, with the highest levels of wall confinement, the overpressures generated in the end ignition experiments increased rapidly as the flame reached the opposite end of the rig to the ignition point. In these instances, the overpressures were significantly greater (over 4 bar) than those produced in equivalent central ignition tests in that part of the test rig.
- In deluge experiments in the 8m wide rig, the overpressures generated in central ignition tests were generally higher than those produced in end ignition tests.
- In experiments in the 12m wide rig, the variation in overpressure within the test rig was associated with both the distance of the ignition source from the nearest open face and the maximum path along which flame acceleration could take place.

External explosion

- In some cases, the combustion of the mixture vented from the rig (the ‘external explosion’) had a significant influence on the peak overpressures generated inside the test rig.

Loading to equipment and structural response

- Safety systems and equipment were installed in the test rig during one of the tests to establish qualitatively their ability to survive a gas explosion. No damage to safety critical equipment occurred that would have compromised its performance.

- As part of a structural response test, a study was performed on the potential for the generation of missiles during a gas explosion. A number of objects were placed in the explosion test rig which were representative of unrestrained components on an offshore topside process module. The maximum distance of travel for one of the items placed in the test rig was 80m (a mounting bracket). Heavier items, such as fire extinguishers and valves, typically travelled distances of up to 10m. The range of overpressures experienced by these items, as recorded by the pressure transducers nearest to the items, was 0.8 - 1.0 bar.

- Six of the test rig wall panels were replaced by specially designed panels, typical of those used offshore. Five of the panels were nominally 4m x 4m and one was divided into two sub-panels, nominally 2m x 4m. The panels were designed with a number of different boundary conditions. The range of overpressures experienced by the panels, as recorded by the pressure transducers nearest to the panels, was 0.8 - 1.7 bar. The panels (depending on their boundary conditions) were designed by yield line theory to have capacities of between 0.34 and 1.0 bar. None of the panels failed in the test, thereby demonstrating the benefits of membrane effects (not accounted for by standard yield line theory). Furthermore, the capacity of the panels exceeded that which would be predicted by yield line theory assuming fully fixed boundary conditions.

Consistency of data and repeatability

- Comparison of overpressure measurements carried out at the same location by independent measurement systems showed very close agreement between the profiles recorded. Comparison of the overpressure, cine and time of flame arrival data showed consistency in the timing of events to within 1 millisecond.

- Comparison of overpressure data obtained from two equivalent high equipment density experiments showed agreement of the peak overpressures to within approximately 10%.

Christian Michelsen Research's Gas Safety Programme

- An information exchange agreement was signed between SCI and CMR (supported by the sponsors of both projects) to enable an exchange of data between Phase 2 and CMR's Gas Safety Programme (GSP 93-96) for the benefit of both projects.

- One of the aims of this data exchange and the link between the two projects was to aid the understanding of scaling effects on gas explosions. The CMR tests (which were at a 1:3.2 scale of the Phase 2 tests) incorporated some of the tests conducted at large scale in Phase 2 (8m wide and Boundary Confinement A) and additional variations such as ignition source location, degree of congestion and gas reactivity. It should be noted that the only item which was not scaled down from the large scale rig was the grating at mezzanine level. The main conclusions from the tests are summarised below:

- In total, four different levels of congestion were investigated. When changing from congestion Level 1 (low equipment density) to Level 4 (high equipment density) an approximate factor of four increase in overpressure was observed at all monitoring locations. For propane, the increase was slightly greater; a factor of 3 to 4 for the central ignition case, when the equipment density was increased from Level 1 to 3. Ignition near the south end of the module led to an increase in overpressures of approximately 4 to 5 for the same change in equipment congestion. Even higher explosion pressures were expected for tests in the Level 4 geometry using propane. However, this configuration was not tested during the current work due to the fear of damage to the test rig.

- For both propane and methane, the maximum overpressures observed for ignition at the south end of the module were twice those observed for central upper deck ignition.
- The tests with ignition at the south end of the module (performed with propane and some of the more severe methane tests) highlighted the likelihood or possibility of high local overpressures near the roof of the north end of the module. This effect was also clearly observed during the large scale tests.
- For all congestion levels, ignition near the centre of the lower deck generated overpressures approximately twice those in similar tests ignited near the centre of the upper deck.
- The tests performed with 'non-standard' ignition positions (largely in the corners of the module) generated interesting observations and underlined the extreme importance of confinement considerations near the ignition source. This proved to be far more important than, for example, the overall flame travel distance. The highest pressures using methane (1.4 bar) were obtained when the explosion was initiated near the roof of the module, in the south east corner (near the north face of the southern control room obstruction). In comparison, ignition in the opposite corner, near the north vent opening, resulted in the lowest pressures (0.17 bar) for the high equipment density (Level 4), despite the greater maximum flame travel distance.
- The effect of gas reactivity was studied by varying the stoichiometry of the gas mixture, using methane. The results revealed that the strongest explosions were obtained for stoichiometric mixtures (equivalence ratio = 1.0). Increasing or decreasing the gas concentration by approximately 25% led to a reduction in the generated explosion overpressures by a factor of between 3 and 4.

The effect of the grating makes a direct comparison of the results found for the low equipment density geometry difficult, although it is believed that the effect of the unscaled grating is less important for the high equipment density geometry. The overpressures generated in the low equipment density geometry are approximately 5 times higher at large scale for central ignition, and 2-2.5 times higher at large scale for end ignition than the corresponding medium scale methane tests. The reason for these differences are partially attributed to scale factors:

- the effects of a different turbulence length scale on combustion
- a longer length of flame propagation where intrinsic flame instabilities can affect the combustion
- the effect of the grating, which was not scaled down from large to medium scale.

For the high equipment density tests with methane, the overpressures generated with central ignition are approximately five times higher at large scale compared to medium scale. This factor is similar to that found for the low equipment density

	tests with methane and the effect of the grating cannot be excluded here either. For end ignition the overpressures are more than 5.5 times higher at large scale than at medium scale with methane. Furthermore, the strong acceleration effects noticed at large scale could not be replicated at medium scale. The results from medium scale propane tests showed that, for congestion Level 3 (which is lower than corresponding congestion level test at large scale), similar effects occurred as those observed at large scale, with methane, and implying that the high acceleration phenomenon observed at large scale is also occurring at medium scale with propane. At low equipment density, medium scale end ignition propane tests generated overpressures equal to those generated in the corresponding large scale methane test. This is partially attributed to the unscaled grating, because the reactivity of propane is slightly low for reproducing at medium scale the effects seen at large scale.