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A critical review of post Piper-Alpha developments in explosion science for the Offshore Industry

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A critical review of post Piper-Alpha developments in explosion science for the Offshore Industry

David C. Bull
Firebrand International Ltd
The Old Rectory
Plough Lane
Christleton
Chester
Cheshire
CH3 7BA

Considerable experimental and theoretical progress in the understanding of explosions in offshore structures has been made over the last decade. This report reviews this progress with special emphasis on the degree of implementation of the new knowledge gained into optimisation of structural design. Remaining areas of uncertainty are highlighted.

The state-of-the-art of knowledge at time of Piper Alpha in

a) explosion loading prediction and

b) explosion response of structures is covered in a brief resume.

Relevant explosion research, worldwide, since Piper Alpha is then reviewed, concentrating on new experimental studies and their interpretation and basic improvements in phenomenological understanding. Progress in modelling and tools available for predicting explosion loading (including ability to cope with inhomogeneous release scenarios, water spray mitigation etc) and explosion response is addressed.

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SUMMARY

Considerable experimental and theoretical progress in the understanding of explosions in offshore structures has been made over the last decade. This report reviews this progress with special emphasis on the degree of implementation of the new knowledge gained into optimisation of structural design. Remaining areas of uncertainty are highlighted.

The state-of-the-art of knowledge at time of Piper Alpha in a) explosion loading prediction and b) explosion response of structures is covered in a brief resume. Relevant explosion research, worldwide, since Piper Alpha is then reviewed, concentrating on new experimental studies and their interpretation and basic improvements in phenomenological understanding. Progress in modelling and tools available for predicting explosion loading (including ability to cope with inhomogeneous release scenarios, water spray mitigation etc) and explosion response is addressed.

Knowledge of deflagration explosions and their impact on offshore structures has increased greatly since the Piper Alpha disaster but large-scale tests in a mock up offshore module revealed explosions more severe than previously recognised. However, new statistical methods address the risk of series of explosion event scenarios. This produces an approach more commensurate with that of quantitative risk analysis and away from the "worst case" scenario. It also puts explosion risks into context - as has long been done for other risk events such as earthquakes, storms etc.

The large-scale tests demonstrated various new aspects of explosion phenomenology not previously specifically observed, and not predicted by the explosion model tools in their then current versions. All explosion models have however now been improved with hindsight.
The basic architecture of CFD codes is now quite old. It may be that adaptive grid meshing would also be a viable future direction for these. Empirical aspects of sub-grid modelling can probably only be improved with further research.

Response calculations must also be made to recognise possibilities of high-pressure excursions due to pressure wave interactions. Further, it is clear that crucial decisions on the nature and magnitude of the loading have to be made before details are available. Applying simple tools at a very early stage can provide design of primary structures, so methods for allowing for future additions of complexity to design are of major importance. Some recent work wherein explosion loading models are directly coupled to response models are discussed and new work which takes this a step further and looks at the effect which a yielding structure has on the progress and nature of the explosion is mentioned.

It is concluded that much of the new knowledge is now available to a wider range of design engineers – for it has promptly been incorporated into know-how transfer tools e.g. computer programs.

Nevertheless, it remains to be demonstrated that explosion response codes predict adequately.

The whole approach is now much more mature, and there is a more widespread understanding of basic explosion knowledge. Some remaining significant gaps in scientific understanding, in technology, and in modelling capability, are identified.

New goal setting legislation has begun to encourage new methods and new technologies - but new research has brought effective mitigation methods.

Water sprays have provided effective mitigation and are here to stay. Water deluge on gas detection is now widely implemented especially in new designs.

As was observed during Phase 1 of the joint industry project, so also now it is clear that commercial considerations put damper on wide rapid know-how dissemination - and this leads to inefficiency. There is widespread knowledge within the circle of those specifically involved in post Piper sponsored project work, JIP Phase 2 etc., but were the new knowledge available to the worldwide scientific community, considerable "gearing" might be achieved with other researchers moving the knowledge forward too.

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The nub of the problem is of making accurate predictions outside domain of experimental knowledge - and it remains. There is still a need so to understand the physics of explosions and their effects on offshore platforms as to permit accurate scaling & prediction. To achieve this, there is a need now to turn attention to the underlying science. Only in this way can a step change in ability and confidence of predictions for such complex situations be achieved. Direct Numerical Simulation may prove to be one of the most useful tools finally to nail problems of scaling - hence significantly improve predictability for large structures.

1.GENERAL INTRODUCTION

In 1991, the state-of-the-art of explosion science knowledge was compared with the prediction requirements of the design and construction engineer for offshore structures and found to be wanting[1]. In two respects this was unsurprising. Firstly, history shows us that many new technologies are developed before mastering each and every one of the technical parameters - indeed if we were to wait until all were understood, there would be no progress. For example steam engines were developed and in wide use before the technology for boiler construction was fully mastered[2], aluminium aircraft built and flown before metal fatigue was widely understood. Technology learning moves apace and is sometimes spurred by accidents.

The explosion science fraternity were at that time looking through a glass darkly. It is particularly apposite to talk of a "fraternity" since there is a finite core of experimentalists and theoreticians working on the explosion theme worldwide and they do generally communicate exceptionally well. In the 1970's there was a flurry of work on gas detonation, inter alia, because at the time it was believed that this might have been the major cause of vapour cloud explosions. Only gas detonation explosions are self-sustained and so only they, it was argued, could occur in wholly unconfined circumstances. This belief was balanced by the dearth of information on the nature, structure and detonability of spherically diverging detonation waves. A wave of experimental and theoretical studies resulted in the knowledge about such detonations increasing in depth and breadth. At the same time this new knowledge showed that detonation was largely to be ruled out as a mechanism as the practical hazard environment as it was so hard to initiate.

Attention then focussed on subsonic, "deflagration" explosions. They are of course not self-sustained but the establishment of the Schelkin mechanism in the early 1980's gave both a theoretical and practical framework for understanding industrial explosions. Over the years a number of vented explosion experiments had been performed and many wholly empirical relationships developed for predicting what part of the adiabatic explosion pressure would occur in practice. The external explosion[3] was first recognised in 1987 so many of the correlations, which assumed the final pressure to be totally due to internal effects, were phenomenologically incorrect. The confined and congested situation found in offshore modules, wherein both adiabatic expansion and turbulent flame acceleration play a role, had scarcely been accessed experimentally. Fuel/air systems need to be studied at large scale since aspects of the phenomenology are just not present at small scale. This does not mean that more reactive systems cannot be studied at smaller scale both to understand the phenomenology and to give indications of large scale behaviour of less reactive systems - but since both flow physics and reaction chemistry and their interactions need to be scaled, this is not easy. Scaling is however an important tool in the armoury, possibly the central one.

Many years before Piper-Alpha, in 1982, large vented explosions had already been carried out by DNV[4] but the information was not widely available, being inhibited by commercial confidentiality of the sponsors. The design of the largest and most scale relevant experiment was, with the wisdom of hindsight only, also seriously flawed[5.] Some small-scale experiments and some scaling studies had also been carried out.

On the modelling front there were empirical venting formulae and computational fluid dynamics (CFD). The latter appeared to be a methodology with potential. Note however that CFD does not solve the fundamental equations of physics and chemistry, and the explosion problem, like all other combustion problems, involves compromise and simplification to tackle it. In particular CFD was and remains one of the few "information transfer vehicles" whereby new aspects of explosion phenomenology discovered by experiment can be incorporated into a predictive tool.

The implementation of knowledge was patchy. Very basic explosion knowledge was not where it needed to be – in the hands of the designer. This led in part to failure to implement the simplest and cost free design optimisation criteria, like fixing the weather cladding lightly so it could act as an explosion vent. Design engineers asked specialists "just give us the pressure and we can do the rest". Thus often an equivalent quasi-static load was assumed. Often plastic deformation was not utilised in design. The maximum credible accident was often taken as one resulting in an overpressure of 1 bar.

In compiling this review the author has examined the large range of reports and scientific papers produced since 1988. He has also conducted interviews with a large number of people active in the field of experimentation and modelling as well as engineers and users of new methodology. As in Phase 1 of the JIP the ground rules were that material regarded as confidential would not be included - although workers were given the option of referring to matter newly researched due to be published shortly. As the title implies, this report is intended no be a critical review not a lexicon. For this reason the author made no attempt to include each and every piece of work. In this area there are an extraordinary number of duplicate publications wherein precisely or essentially the same matter has been published in a two or more different locations. Again only one reference will be shown, where possible the earliest. Further, in one particular scientific area, that of CFD modelling, a number of papers seem to fulfil an advertising role rather than add to the sum of knowledge. For this review to retain its critical nature, therefore the author has chosen a selective approach in this department. There are also a number of "me too" publications where different institutions have tackled a problem with essentially the same approach.

1.1 THE STATE-OF-THE-ART OF KNOWLEDGE AT TIME OF PIPER ALPHA BOTH IN EXPLOSION LOADING PREDICTION AND IN EXPLOSION RESPONSE OF STRUCTURES.

1.1.1 Explosion Loading

Following the Piper Alpha disaster in July 1988, a group of concerned individual companies together with the UK and Norwegian regulators (UKHSE and NPD), set about organising a joint industry Project on Fire and Explosion for topside structures ("JIP Phase 1")[1]. The aim of the project, which ran from May 1990 to Feb 1991, was to identify the best available knowledge worldwide and to identify significant gaps in that knowledge base leading to uncertainty in design, as well as to devise future programmes aimed at reducing the uncertainty level. The output of that project now comprises 26 reports and a "1991" guidance document[5]. The point if the present study is, starting with that state of the art, critically to review the work which has taken place and to appraise the new knowledge base as well as the extent to which know how transfer had taken place.

Briefly the situation at the outset was well summarised in the JIP Phase 1 reports[1] as:

"The only experimental data of any relevance to offshore explosions is very scant and its applicability is very limited. All the data overlook many factors of importance to the offshore problem. In particular the configurations are idealised. Only the scantiest information exists on truly representative geometries and bounds to experimental scaling still to be set."

"Not all models have been published in detail. In general no neutral evaluation of applicability has been made".

"No independent assessment has been made of the solution accuracies of the numerical packages currently being used……………"

"There is uncertainty in general in the accuracy of "subgrid" models used in numerical codes to substitute for a description of the physical processes which are occurring on length scales below the resolution accuracy of the numerical technique. This may be particularly important with regard to small structures."

The significance of external explosion first observed by Harrison[3] was not widely understood and many models had failed to implement it.

1.1.2 Mitigation

Even explosion mitigation by design optimisation was not universal practice at that time.
Work on water spray methods had commenced but, as quoted in ref 1(No 595):
" The interaction of suppressant with an explosion flame is complex and poorly understood. No suppressant system has been assessed in geometries identical to those in offshore modules though water sprays have been used in similar geometries."

1.1.3 Explosion Response

Ref 1(No 594) sums up the following position in 1991*:*
"There is no detailed understanding of the loads experienced by structures in the wide range of transient blast waves capable of being generated in offshore explosions" and

"Essentially no data exist which improve the understanding of structural loads experienced in explosions relevant to offshore problems".

1.1.4 Guidance

For a summary of the information available to the design engineer immediately after Phase 1 of the Joint Industry Project on Fire and Explosion for Topside Structures, the reader is referred to reference 6, the guidance document issued for the industry.

2. REVIEW OF RELEVANT EXPLOSION RESEARCH SINCE PIPER ALPHA

2.1 EXPERIMENTATION

The central problem as described in the reports of JIP phase 1 is of making projections about the behaviour of combustion waves in very large structures, when our knowledge base derives almost exclusively from small-scale experiment and our understanding of the physics and chemistry is such that it is realised that different parameters scale in different ways. Experimental progress over the last decade, intended to permit better future prediction of full scale behaviour, can be broadly classified into three categories: a) experiments at smaller scale designed to be used in conjunction with albeit limited understanding of scaling behaviour b) experiments designed to illustrate different aspects of the explosion science to improve understanding and ability to scale on a sound physical basis c) large or full scale tests, designed to exhibit fully the phenomenology in real situations . The latter provide further input to understanding scaling but also permit empirical comparison.

2.1.1 .Scale Model Experiments

An important new avenue opened up in the search for more realistic scenarios. How does gas build up from leaks in an offshore module? What is the result of explosions in such cases and how far does this deviate from the well-mixed stoicheiometric mix filling the module scenario? Van Wingerden et al[7] reported an experimental study of gas dispersion in a 1/5 scale model of an offshore module and concluded that for medium and large scale jet releases the dispersion in a module is dominated by the jet but the actual gas concentration depends upon the ventilation whilst for smaller release both dispersion and gas concentration are dominated by natural ventilation. Larger scale tests and explosions in such releases have since been carried out (see below).

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The topic of explosion scaling, first proposed by Taylor & Hirst[8] (1989), showed how, subject to various limitations, the fractal nature of explosion flames could permit the conduct of experiments at a physically smaller scale with a more reactive gas (say ethane) and relate the results to full scale behaviour with a less reactive gas (say natural gas). The method was used to effect in design of the Troll platform by the experiments of Samuels[9] using a 1/12 scale model. Other laboratories had tried variants on this method using vitiated air (Oxygen enrichment), rather than more reactive hydrocarbons, to increase the reactivity e.g. Catlin[10], Johnson et al [11] .These have been less satisfactory to perform because of the necessity of accurately dosing both fuel and oxygen in the mixture.
The method has received relatively little attention recently. An exception to this has been the work of Phylaktou and Andrews[12,13] and Gardner et al[14] who have pursued the topic in interesting ways. In particular the application of multi-variant regression analysis to the MERGE[15,16] data gave interesting new empirical insight into the scaling problem.

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2.1.2 Explosion Science Experiments

For open structures, the MERGE experiments series reported by Merx et al [15,16], mark an important waypoint. In these experiments commissioned by the CEC, explosions were carried out in a standardised congested but unconfined structure at various scales by a number of laboratories. They included experiments with jet releases as well as homogeneous mixtures. They also provided information on the strengths and limitations of scaling. Unexpectedly high pressures were experienced in some of the tests and nearly all of the then currently available models were tested, found wanting, but subsequently improved (Popat[17]).

Snowdon et al[18] report 42 experiments in confined and unconfined experimental rigs at medium scale which have been used to improve the understanding of the flame acceleration processes, different obstacle fields and venting situations as well as providing an additional; data set for model validation/improvement. Ibrahim and coworkers[19-21] have provided interesting new laboratory-scale experimental data sets using advanced laser diagnostics both to probe the detail of flame-obstacle interactions and to examine flow in turbulent wakes[22,23].They show *inter alia* how the vortex pairs formed behind obstacles cause unburned as mixture to be trapped and burned after flame reconnection behind the vortex and how this effect differs for obstacles of different geometry and mixture concentration. The data sets should be valuable for verification of those models which are capable of including this important level of detail.

The SOLVEX series of experiments[5] carried out in 1993 comprised large (500m^3) scale vented explosion experiments with well-defined geometries and 0, 1 or 2 rows of pipe obstacles. They provided a unique data set for model validation and were used initially for detailed improvements in Cates'[24] phenomenological explosion model, SCOPE. They also, incidentally, dispelled the myth that large-scale experiments are poorly repeatable due to various stochastic effects! By attention to all aspects of detail in gas mixing, firing etc the test-to-test repeatability obtained in every aspect of the explosion history was truly excellent (<1%) putting many smaller experiments to shame.

A recent experimental study by Chamberlain and Rowson[25] addresses the topic of partially filled enclosures. Very little data indeed existed on this topic until this study. The experiments they reported were at medium scale and comprised a confined/vented rig 2.5 m long x 1.5m high x 2.25m wide with a 50% area vent at one end. Up to 7 rows of 50x6mm steel bar obstacles were used and partial fills of 10,21,31,41 63 and 100% were used with methane 1.1x stoicheomtric and end ignition in each case. Similarly an open "unconfined " rig was used which comprised a steel lattice framework of 1m cube cells on a 3mx3m footprint. Removable steel plates could form a roof over the structure thus giving the combustion process cylindrically divergent geometry. Partial fills of 2, 5 and 12% were attained with this rig. and experiments performed with methane propane and ethene, using central ignition. The authors concluded that at high levels of partial filling the overpressure generated was similar to that attained by totally filling the confined area. At low levels the overpressure was considerably reduced. Also in these cases the external explosion no longer occurs.

2.1.3 Two Phase explosions

This area of work has received comparatively little intensive experimental study. This is small wonder considering just how difficult it is to separate the variables and make a proper scientific analysis. Spray and aerosol systems are known as time dependant systems because, from the moment of generation, their characteristics change with time. Thus the original droplet size distribution will change by the processes of droplet coalescence, droplet shear and shattering as well as evaporation etc. The concentration of fuel in air will vary because of plating out of droplets on to walls or other surfaces, settling under gravity and so on. The process of generating such material, e.g. due to fuel emerging as a jet following rupture of a line containing fuel under pressure, will also generate turbulence within the fuel/air mixture and this turbulence will itself decay with time. It is clear then that the time of ignition following release will be a very significant variable governing the nature of the explosion – even more so than is the case for gas releases.

At least since the Flixborough explosion in which cyclohexane was released as (initially) an aerosol cloud the questions have been posed "is their something special about aerosol explosions?" Are they worse? Early work on supersonic explosion (detonation) of aerosol mixtures[26] indicated that the behaviour of such systems in unconfined explosions was governed by the volatility of the liquid component. Involatile liquids proved almost impossibly difficult to detonate. Yet earlier work (1954) of Burgoyne and Cohen[27] showed that for very fine droplet systems having droplets of less than 10 μ, the flammability behaviour was rather like a simple extension of the lower flammable limit below the normal flashpoint barrier. Though well known to combustion scientists[28], the significance of this conclusion for the environment of the practical hazard, and specifically in the domain of areas classification, was largely missed until the work of Bowen and Shirvill[29,30]in 1994. These authors proposed ways in which area classification must be modified if escapes of finely atomised liquids below their flashpoint are foreseen as reasonable scenarios.

Bowen et al[31] addressed the case of aerosol explosions offshore by performing experiments in a 1/6th scale version of the Solvex[5] rig. Interestingly, using the technique of image analysis they were also able to obtain a unique visualisation of the external vortex cloud throughout its generation and combustion process. This was made possible because the aerosol clouds, unlike gas clouds, are visible to the naked eye/camera. The result of their experiments however was somewhat similar to the earlier conclusion for aerosol detonation i.e. that the behaviour is governed by the volatility of the fuel. This is because both explosion flame processes are fast (although detonation is more than an order of magnitude faster than deflagration) relative to many of the mixing processes. Combustion of that part of the fuel not participating in the flame front will continue to occur at longer times until all is consumed.

The general conclusion of our current knowledge is that aerosol explosions may generally be modelled conservatively and in many cases extremely conservatively by considering them as gas explosions. Some laboratory and theoretical studies do indicate that this general conclusion may not always be valid for aerosols whose droplet sizes lie on the 20 – 30μ range. So some work on this theme continues, Bowen and Cameron[327] have recently reviewed the state of the art of the whole topic area of hydrocarbon aerosol explosions

2.1.4 Full Size Tests.

An important study was that of Cleaver et al[33] who, following an earlier theoretical examination of the physics of the problem[34] used a mock-up of an offshore module created for explosion experiments and state of the art visualisation and sensing techniques to measure both flow patterns of natural ventilation under wind speeds between 0.9 and 8.6m/s and the resulting concentration contours for well defined steady state leaks of a methane/nitrogen mixture (diluents avoid flammable hazard) in the range 0.5 – 10kg/s. a range typical of those which might occur in a process module Experimentally, release orientation and position was varied as were 3 different rig configurations.

Landmark[35-40] large-scale tests have been carried out in a mock up of a full-scale offshore module (28m x 12m x 8 m) as part of the subsequent Phases of the JIP. These Phases are known as Phase 2, Phase 3a and Phase 3b,

Briefly, Phase 2, completed in 1997 and reported in ref. 35, comprised 27 experiments and showed that high overpressures could be generated for certain configurations and that water sprays activated prior to ignition could significantly reduce the overpressures.

Phase 3a was an HSE initiative to obtain further data and to explore the mechanism, which led to particularly high overpressures and ways of mitigating them it, has been reported in ref 40
The overall objectives were to provide information on the reduction of explosion over pressures in the design of new and modified offshore installations. It was also intended to identify mitigation measures to reduce explosion overpressures in existing installations and to provide further test days and for use in validation of explosion models.

The repeatability study reported in ref 38 and 39 (also contains some of the Phase 3a results). Despite their great expense, over 45 explosion experiments have been carried out in this rig in a wide variety of configurations, congestion and confinement ignition points, mitigation measures etc. Backed up by smaller scaled experiments performed by CMR these data also now give input to scaling considerations. The tests have been used to test the prediction ability of models and, where found wanting, their validation and calibration. They also help in understanding some aspects of explosion scaling. They yielded unexpectedly large overpressures in some configurations and these, and other aspects of explosion phenomenology not heretofore expressly tested, were manifest. Important here for example was that it proved necessary to re-examine the relative roles of two factors which cause flame wrinkling viz flame induced turbulence in the unburnt gas and obstacle induced flame folding.

It is anticipated that further reports of this project will gradually be made public.

Some idea of the repeatability[39] of the tests has also recently been obtained. This is important because the significance of some of the results could have been misinterpreted.

2.1 EXPLOSION MITIGATION

2.2.1 Mitigation By Design

The JIP Phase 1 identified "mitigation by design" as one of the important and cost effective ways of reducing explosion over pressure. Bakke and van Wingerden[41] give a concise account of account of the best advice that experts on current platform-ventilation and explosion science could then give. This 1992 work has not been overtaken by subsequent research although much more experience has now been gained. A "classic" case of mitigation by design optimisation has recently been illustrated by Paterson et al[42]. In the design of the BP ETAP platform against explosion they showed how in one instance a layout with pig launchers in a North South Direction gave a computed (CFD) overpressure of over 4 bar, with the equipment in east west direction maximum pressures of 0.5 bar were attained. The paper appears to be a good illustration of how design optimisation for explosion at an early stage results in low or no cost optimisation and can also bring design simplification. The authors also correctly draw attention to the pitfalls of failing to take into account vendors skids, cable racks, etc - the devil being in the detail. JIP Phase 2 sheds light on this.

2.2.2 Water Sprays

Very considerable effort has been expended on this theme over the last decade with experimental work at BG[43,44] CMR[45-47] Aberystwyth[48] and other centres. The paper by Thomas[48] however gives a particularly clear exposition of the way in which the technique functions and also presents results from recent fundamental studies that illustrate and quantify the basic chemical and physical processes by which water spray mitigation occurs. In a nutshell it has been shown that large droplets are sheared by the high velocity flow in the flame acceleration process, breaking them up into very fine droplets which are able to act swiftly on the explosion flame. The optimisation process for system design then comprises getting a water spray of sufficient loading density in the right place with a droplet size amenable to forming micro droplets by the stripping process.

Whilst many studies and most implementations have concentrated on the use of area deluge methods as implemented for fire protection, the delivery of water drops already in the fine mist format necessary for flame reduction is an obvious alternative – if it can be achieved. Over the years a number of fine mist devices have been developed and tested. One device uses stored thermal energy in superheated water at 180^{o}C, svp 10bar. On discharge, immediate flashing occurs and many droplets formed are in the 10 micron range with a tail of non-flashed material as large as 100 microns. Most recently however one of these devices, Micromist[49,50], has been tested in a medium scaled replica of an offshore module. Tam et al[50] used 4 devices two on the roof discharging downwards and two discharging horizontally in a rage of directions. Different ignition to discharge times (50, 100,150 ms) were used and both central and end ignition tried. The tests demonstrated that such devices could arrest a propagating flame and totally suppressed an explosion within a confined module. The results showed that the performance of the mist curtain lies somewhere between that of a diluent and a perfect suppressant. If the mist curtain was deployed over only the upper half of the module then the effect was negative.
There remain a number of questions to be answered, especially those concerned with the number and position of devices to be deployed, reliability of device and trigger system, maintenance required etc. Nevertheless the idea of a device with localised intelligence is appealing.

Catlin[51,52] has recently reported a quasi-passive method of generating water sprays in the path of an explosion. Basically the patented method (not yet commercially realised) uses trays of water. It has been tested in a 5x0.3x0.3m explosion duct. It was shown that the blast wind of an accelerated flame in explosion conditions causes water to be sprayed out of the device and into the flame. Superficially the principle is similar to that used in some mining situations where troughs or bags of water have been used to provide a similar passive mitigation device. This tray system is however more sophisticated in that by optimising the shape of the semi-closed containers it uses pressure differential developed in the flow and transmitted through inlet holes to the surface of the water to cause the water to exit though outlet orifices. The efficiency of the device increases with increasing flame speed due to the production of smaller droplets just as was found for active drop spraying methods and, as with these methods, the presence of the device actually causes a slight increase in flame rate at low flame speed. It can be seen that with appropriate deployment it is possible that this method may be applicable to offshore structures and process plant.

2.2.3 Barrier Mitigation Methods

In Phase 1, various other control methods were briefly alluded to. There has been little practical progress on many of the methods except design optimisation. Tam[53] has however recently reviewed barrier methods for explosion control and the "quantitative " effect which CFD predictions indicate they may have. Basically the barrier has the effect of controlling the severity of the consequences of a potential gas explosion. It does so by control of the flammable inventory e.g. segregating a section where there is a release from one where there is none (Tam calls these cloud control barriers) or controlling the development of an explosion. By venting it etc (Tam calls these development control barriers).
Barriers include:
Hard barriers – blast walls
Semi hard barriers – Weak walls
Soft Barriers – Membranes (as incorporated in BP Magnus Platform)
Soft and Suppressive barriers – both suppressive and non-suppressive of the explosion

2.2.4 Statistical Treatments to mitigate explosion design case

A major new development is that of statistical treatments. One of the paradoxes, which previously existed in explosion hazard assessment, was that there was a major discrepancy between probabilistic hazard appraisal and the pessimistic maximum credible accident approach to explosion loading. The recent development of loading tools which take into account the gas cloud size, ignition locations etc etc., was necessitated in part by some of the unacceptable pressures observed in idealised tests in realistic structures. They have however put explosion prediction on the same basis as many other method matters in mechanical engineering e.g. wind load wave loads earthquake severity/ frequency. Hoiset & Hijtager[54], Corr et al[55,56], suggest three levels of event frequency, so 3 different limit states should occur. For high probability events (>10^{-3} PA), all safety critical systems should remain intact, function etc.; for intermediate events (10^{-4}PA), only selected safety critical system designed survive - and for low probability events (10^{-5}PA), decks and steel work plastically deform, are severely distorted but the structure has a > 90 % survival chance.

Shell's exceedence method was alluded to by Savage[57] and recently presented by Puttock[58] . Briefly, the method acknowledges the shortcomings of concentrating on the "worst case" and instead assigns a frequency to both worst case and other pressure loading levels. The following parameters may vary from incident to incident:

Location of leak,
Material released (composition) and its state (gas, liquid, two phase)
Hole size, leak rate and orientation
Wind speed and direction (influence flammable cloud size)
Ignition location

Ignition delay after release
Deluge on or off.

A Monte Carlo method is used, running an explosion model many thousands of times and varying all of the input parameters. Puttock used the phenomenological model SCOPE, which takes a run time of only a few seconds. The output of the process is to generate specific exceedence curves. These may be e.g. frequency of exceedence per year of any overpressure - either for a median pressure or for the highest localised pressure. Alternatively, probability of exceedence versus median overpressure or impulse can be shown. Puttock shows for one offshore module that whilst scenarios for generation of up to 10 bar can be envisaged, these are at frequency of exceedence level of 10^{-5}/yr. At 10^{-4}/yr exceedence the level is only 1 bar.

Others e.g. Talberg et al[59] have described probabilistic approaches to exceedence curve generation using CFD codes. However because of the large run times associated with the far more complex models, the studies are limited to a few hundred runs and cannot attain the degree of statistical significance which the many thousands of runs used by Puttock with the phenomenological model. Hoiset et al[60] describe a similar approach and show the significance of an improved time-dependant ignition model.

2.3 Explosion Response

CFD can provide maximum overpressure anywhere, overpressure at given points, kinetic energy at given points, average pressure on walls. Further more, drag loading on equipment can also be calculated.

Savage et al[57] report using non-linear dynamic structural analysis tools to identify redundant and any weak links in the support system, and ultimate capacities of structural elements and blast wall pressure impulse duration were computed. Steel blast walls are increasingly used designed to produce a plastic hinge at the connections limiting load transmission to the structure (SCI Interim Guidance[6]). The structural response cannot be covered by a single design case. Rather for components that respond dynamically a range of loading cases need be considered to provide a robust structure which will survive all events. Primary steel joints have been designed to match the full load carrying capacity of the attached member and in this way full plasticity can be achieved to cater for high plastic strains during a blast or other major accident event. Increased joint fixity in critical areas was used to limit deformations and to provide reserve strength. The primary and secondary structures were designed such that weaknesses were always in the secondary elements rather than the members performing primary functions. Where flexibility is required pinned joints were specified.

Hoiset et al[60] used a CFD code (EXSIM) on three offshore modules with 10, 000 different simulations. From the data so generated they endeavoured to produce some correlations and rules of thumb useful to the structural design process. They concluded that there seems to be an approximately linear relation between the pressure or impulse and the gas volume. There seems to be an inverse relation between explosion pressure and explosion duration - but the effect is not so clear for explosion impulse. Short explosion durations are uncommon and whilst loading rates vary a lot they generally fall in the range 1.5 – 90 bar/s.

Relatively little novel experimental work on structural response has been reported recently. An HSE report by Trim et al[61] however describes, data only, measurements of the response of vessel support systems to explosion loading. The authors used two strain gauged large reaction vessels one empty the other filled with water, set in the path of the blast emerging from a bang box type vented explosion. Burgan[62] reports an assessment exercise of the capability and accuracy of 8 available techniques (6 finite element analysis and 2 simpler methods) for the prediction of structural response of stiffened and unstiffened steel panels to explosion loads.

Phase 2 of the JIP included one explosion test in which seven blast panels comprising stiffened plate construction were installed in one side of the rig and time-displacement profile of the centre of each panel and residual deflection at 25 places on the panel surface were measured. The results, for such a simple structure, are not impressive.

Shearer et al[63] are amongst few who have analysed the results of the Joint Industry Project on Fire and Explosion for Topside Structures Phase 2 and 3a data in some depth. Their analysis led them to state that the maximum overpressure as currently defied lacked meaning when isolated from the response of a structure. A structure with low resonant frequency <50Hz receives far less load than a stiffer structure >100Hz. The indiscrimate use of headline peak overpressures could lead not only to the wrong conclusions but also to the wrong remedial measure being adopted. Thus e.g. global stiffening of a blast wall could actually make it more vulnerable to failure in gas explosions.

One useful development reported in Norway at least, is the ability directly to interface explosion loading CFD codes with response models thus deriving full benefit of the calculated loading history. It remains to be demonstrated that explosion response codes predict adequately, and comparison between prediction and performance for more complex structures are eagerly awaited.

One significant new development has been touched upon by Robertson et al[64] at the 2000 ERA conference. These authors address for the first time using a CFD code (AUTOREAGAS) and a hydrocode, AUTODYN 3 D, the coupled Blast-Structure interaction including the movement of the structure as it is loaded. The model disposition was chosen such that blast provided loading to the structure and was itself affected by the response of the structure. They showed that, whilst the cubic structure they examined deformed, the pressure loadings are actually much reduced - as the blast wave is no longer reflecting from a rigid surface! The resulting reduction in the maximum deflection observed is some 25% or so compared to the assumption that load and response were not coupled. The authors studied a very simple structure although Cant reports that similar coupling experiments he performed with a numerical analysis tool gave reductions for more complex structures. It would certainly be worth investigation whether such effects are generally benign or whether there are downsides - and whether it would be worthwhile taking them into account.

Some new large-scale experiments are in hand at the time of writing[65] and form part of the “Phase 3b” JIP. These experiments utilize a bang box (4.5mx4.5mx9m) to provide well controlled gas explosions, having both shocked and non shocked blast waves, and set a well instrumented target in the path of the blast. The target is a supported cubic framework on which instrumented steel panels are mounted. It is so instrumented as to permit measurements on front side and rear faces. It is envisaged that the well-defined and carefully controlled large-scale experiments will address key uncertainties in the interaction of a gas explosion blast wave with structures as for example an offshore temporary refuge.

3. REVIEW OF PROGRESS IN MODELLING AND TOOLS AVAILABLE

3.1 GUIDELINES

The idea of formulating simple guidelines and assessment tools for predicting vapour cloud explosions has been around for some time. Early examples of methods, which supplant the inappropriate TNT approach, are the "Multi energy" method[66,67] and the Baker method[68]. For the first time, Cates' (1991) Congestion Assessment Method[69] gave a clear method for identifying source pressure from the plant layout and fuel type. Originally formulated for open structures like onshore plant, it was elaborated to encompass all chemical types by Barton[70]. Putttock[71,72] has recently revised the congestion assessment method now known as CAM2 and whilst the revised formulation may have lost some of the transparent elegancy of Cates' original formulation, it is now applicable for screening purposes in both open and enclosed offshore structures. It is now incorporates much more of up to date explosion dynamics knowledge that other models in this group.

3.2 PHENOMENOLOGICAL

Several phenomenological models were identified in the JIP Phase 1 Reports[1] .More recently, Cleaver & Robinson[73] have extended the simple theory of Deshaises et al[74] and successfully modelled some of the data on open congested structures investigated in the MERGE project.

Of the large range of such models identified in the JIP Phase 1, a more restricted number were still in use during Phase 2. Whilst many of the models are proprietary and still available for use, open literature search since the early 90's yields information on continuous development for only one of these models. Puttock et al[75] describe SCOPE 3, which, building upon the original formulation of Cates and Samuels[76] , has taken into account effects of obstacle complexity - phenomena not previously realised in earlier versions. At the same time the authors have taken into account a revised turbulent burning velocity formulation, allowed for vents at rear walls, treatment of gas mixtures and of temperatures and humidity variations. After validation against over 300 experiments, the prediction of the data sets and the predictability in blind tests is not significantly inferior to the much more complex CFD calculations - but this type of model is so simple to run that batch running permits large numbers of combinations of ignition position geometry etc to be assessed.

3.3 COMPUTATIONAL FLUID DYNAMIC

A detailed specialist's review of the state-of-the art of explosion modelling has recently been prepared[77] and should eventually be published. It is not therefore the intention of the current report to review these models in such depth rather to point directly at strengths and weaknesses availability and future directions.

The work of Popat et al[17] represents an important measure of the state-of-the-art of CFD based explosion models at the time the comparison was carried out (1994). In this paper the theoretical and numerical basis of 5 different CFD models (from 5 of the 8 organisations involved in the MERGE study) are described and results are given of a comparison exercise of model predictions against calculations chosen to test the accuracy of the various physical sub models. A development phase during which models were improved with the hindsight of results on small and medium scale experiments with methane and propane, was conducted.

Finally the models were used to simulate large-scale experiments prior to the experiments. This type of exercise, which has also been carried out in the JIP phase 2 etc, has its advantages and disadvantages. Used in this paper however it served to highlight areas of uncertainty in the physics. Whilst predictions of maximum overpressure and duration differed widely, the trends were well predicted, showing smaller durations for higher overpressures. The study identified those sub grid models which are most sensitive to the size of the computational grid cells as the turbulence- and ignition-sub models, and the necessity of having sufficient cells in the reaction zone for accurate prediction of the burning velocity - pointing to fine gridding or adaptive gridding.

The importance of grid refinement on explosion prediction in even a very simple structure (10m long 2.5m dia cylindrical vessel with 5 orifice plates) was demonstrated by Catlin et al[78] who used an adaptive grid algorithm allowing the finite volume grid to be refined and redefined locally within the flow accurately to resolve flame fronts recirculation zones and shear layers. An important new method for local grid refinement has recently been presented by Gjesdal[79] who describes a method to improve the simulation of dispersing jets in an area close to a leak. The approach should be applicable to a wider range of problems including multispecies gases turbulence compressibility and complex geometries. It was also concluded that there are empirical aspects of the sub grid modelling which can only be improved with further research.

Comparison of CFD results against experimental data in a 3 D module geometry showed "good" agreement, Hjertager & Solberg[80]. "Good" here, as with most explosion model comparisons, means all but 3 data points out of 31 lie within a factor two of the experimental points. Using the statistical method of Saeter et al[71], the EXSIM code over-predicted by 3% and there is a 95% confidence that the mean max overpressure lies within +/-46% of the predicted value.

How good is good enough? Following all the improvements and fixes resulting from learning as a result to the JIP Phase 2, Naamansen et al[82] turn back to a well tried experimental system which is capable of simple geometric approaches, that of baffled vented enclosures. Whilst both EXSIM, the purpose built Explosion code and CFX, the general purpose code, simulated observed experimental trends, they almost always over-predicted. The calculated explosion overpressure lies within a factor of 2. Neither EXSIM nor CFX show convincing grid independence. Even though the grid chosen is very fine, the solution still seems to depend upon it. It is concluded that in future a different numerical strategy must be adopted viz. intensive gridding.

Some important experimental and theoretical studies have addressed the inadequacies of the physics in early versions of CFD models. Kong and Sand[83] address for the first time the gas explosion driven transient near-wake flows, by using Laser Doppler Anemometry (LDA) in a one-dimensional channel, for methane explosions. Interestingly they found that maximum turbulence velocities obtained in the near wake of cylinders and square obstacles were lower than those in steady upstream flows. Further, due to the sensitivity of the vortex shedding and the vortex motion to upstream and downstream disturbances, velocity time histories in the near-wake region are not reproducible even when the upstream flow is well reproduced. They conclude that calculation of turbulence in such transient flows should be based upon each individual explosion rather than ensemble averaging. It is certainly a fact that unlike in models, real explosions have real instantaneous flames which encounter instantaneous turbules not average flames encountering average turbulence levels!

The effects of any pre-existing turbulence which occurs e.g. on release of gas as a jet were studied by van Wingerden et al[84-86] in a medium scale version of a petrochemical installation. They showed that turbulence due to the release or even wind may lead to an increase in the explosion overpressure - presumably by making the flame burn faster earlier, thus increasing the flame acceleration. The effect of initial turbulence is only strong when ignition is within the turbulent jet and increases with release rate. Outside the zone of influence of the turbulent jet the effects are limited. Windergen et al[84] also briefly address the problem of partially filled enclosure. This matter has recently been extensively studied experimentally by Chamberlain and Rowson[25] as discussed in 2.1.2 above.

As mentioned in 1.1.1, the external explosion was first identified by Harrison and Eyre but at the time of the Phase 1 study this was still not widely recognised and many explosion codes had not extended their domain to include it. Now it is universally recognised as a contributor to the total internal load and also as posing a hazard to external structures, walkways etc. Van Wingerden[85] , for example, describe how FLACS 94 was extended to include this feature whilst EXSIM and SCOPE models have also always included it. A recent more detailed study modelling the interaction between the external and internal explosions was provided by Marsano et al [87]

For more open structures, the directional, decaying blast outside the plant can also usefully be predicted by CFD, e.g. van Wingerden[86]. Alternatively simpler tools like SCOPE 3[75] can be used.

It may well be asked whether the somewhat dated architecture of some CFD codes could efficiently be improved in a way to span the gap between the current state of the art and Direct Numerical Simulation (DNS) techniques, discussed in the next section? With the advent of very powerful computers Large Eddy Simulation (LES) has now become a viable tool for simulating flow instabilities and unsteady process in reacting as well as non-reacting flow. This has recently been demonstrated by Kirkpatrick et al[88] in an albeit simple case. These workers modelled experiments in a box (0.545x 0.195x0.195m) containing 20 litres of LPG/air mixtures and showed good agreement. The LES method allows a CFD code to generate its own length scales that can resolve so sub-grid turbulence models only need be invoked for scales smaller than a critical dimension. As reported elsewhere[77], it is a premise in the LES method that there exists a minimum length scale beyond which further grid refinement will not lead to significant changes in the turbulent flow properties of interest to explosion dynamics and that this minimum scale is larger than the resolution required for DNS simulation. Thus has however yet to be demonstrated.

3.4 DIRECT NUMERICAL SIMULATION

This methodology has been well described by Cant[89]. Briefly, it is the only truly fundamental theoretical approach and its use has already contributed to improving subsets of other models. Solving the Navier Stokes equations which govern fluid flow without averaging is the most accurate approach to turbulence. In this approach the whole range of length and time scales are solved, without any modelling approximation. The accuracy of this method makes it a very powerful tool for approaching turbulent flow and an important basis for the more complex problem of reactive turbulent flow. Even so chemistry is usually incorporated by look-up approaches to more complex chemical models run externally. (e.g. Chemkin [90]). The inhibition to its wide adoption is the large computer source requirement. This places a restriction on the size of geometry which can be tackled. Given current computer resources DNS is not now a successor to other engineering tools. Its current usefulness resides in the large amount of detail that can be obtained about a turbulent flow field. The detailed time and space resolution which DNS calculations give exceed in many respects even the detailed data acquired by all but the most highly and intensively instrumented experiments. They therefore give truly new insight into the physics of the processes involved.

The novel unstructured solution adaptive mesh system adopted by Birkby et al [91] shows significant benefits in terms of accuracy and computational efficiency. The method allows important features of the solution to be resolved closes to the flame and in the vicinity of obstacle wakes and shear layers where turbulence levels are high The methodology has been applied to an impressive number of test cases[92] and can even provide a qualitatively correct description of the transition to detonation. Combining this model with a virtual reality interface helps to give increased physical insight[93]. The rate of progress in this area is impressive indeed. It will certainly find application in elucidating further the problem of scaling of explosions.

3.5 FUTURE MODELLING DIRECTIONS

The recent report[77] points towards improvements needed both a) in the regime between mild ignition and the fully turbulent combustion. i.e. the early stages of explosion development and in improved calculations for fully turbulent flames prior to the development of shock waves.
For a), specifically improvement should be sought in the representation of laminar flame propagation, flame distortion due to diffusion /hydrodynamic instabilities, and flame interaction with acoustic waves were recommended for study. For b), instabilities due to flame interaction with an accelerating flow, flame pinching and flame interactions with acoustic waves and pressure fluctuations were suggested.

4. THE CURRENT DEGREE OF IMPLEMENTATION

As Renwick[94] suggests, there is no doubt that the new goal setting legislation put in place as a result of Piper Alpha has begun to encourage new methods and new technologies. This mirrors the important historical record of the role of the regulator in improving intrinsic safety of technology[2]. Large scale research has shown that explosions may be more severe than was previously recognised but also new research has brought about effective mitigation methods.

Statistical methods are also putting the risks into context - just as have been done previously by other risk events e.g. wave impact, earthquake etc. The whole approach is becoming more mature with a more widespread understanding of basic explosion knowledge by designers and safety case writers.

Water deluge on gas detection is becoming widely implemented especially in new designs.

As Savage[57] points out one of the paradoxes in explosion management is that crucial decisions on the nature and magnitude of the loading have to be made before detailed predictions are available Application of simple tools at a very early stage can provide the design of primary structures. Explosion assessments to provide an important input to design - Tam BP says that it is one of the crucial features at heads of design stage and needs to be signed off and approved in the same way as all major platform parameters. The idea of predicting for the effect of future additions of complexity to the design, is of major importance.

It has been proposed that the guidelines[6], issued after Phase 1 of the JIP on Fire and Explosion for Topside Structures should now be updated, in the light of the new knowledge gained as a result of the Phase 2 and 3 work. At the time of writing this is in hand.

There can be no question but that the knowledge of deflagration explosions and their impact on offshore structures has increased hugely since the Piper Alpha disaster. Furthermore and most importantly much of that new knowledge is available to a wider range of design engineers and has been incorporated into know how transfer tools such as computer programmes.

5. A LOOK FORWARD

In this section we examine the question "are there still significant gaps in our understanding?" In the context of offshore safety the word *significant* is here assigned the very specific meaning of significance to the processes of safe design and operation as well as minimised loss to life and limb in event of accidental explosion. (Of course in a topic as complex as explosion science there will be gaps in the total knowledge base of how the whole process works for the foreseeable future).

Many of the specific problems identified in the Post Piper Alpha JIP including those listed in section 1.1 have been addressed, at least in part, and the whole area may be seen as more mature. Nevertheless a need so to understand the physics of explosions and their effects on offshore platforms as to permit accurate scaling and prediction has not yet conclusively been met. The central problem of making predictions outside the domain of experimental knowledge remains. This is the nub of the problem. The large-scale experiments of Phase 2 introduced new aspects of explosion phenomenology not observed heretofore and not predicted by any of the explosion model tools in their then current versions. With hindsight the explosion models have been improved. As a simple example, one of the important modifications being the correct partitioning of the roles of obstacle driven turbulence and flame folding on passage through obstacle arrays. The extreme sensitivity to small obstacles was also first demonstrated in these large-scale experiments. We have described CFD models as "an efficient knowledge-transfer vehicle", and they have proved better and more useful in this role than as a predictor for wholly novel experiments.

The basic architecture of existing CFD codes is now quite old. It may be that adaptive grid meshing would also be a viable future direction for these. Use of large eddy simulation methods may also bring about added realism to the description of turbulent flow.

Direct Numerical Simulation may prove to be one of the most useful tools in our armoury to finally nail the problems of scaling and hence significantly improve predictability for large structures in the future. It is also an important tool in getting the most out of existing experimental databases.

Response calculations need to be at least aware of the possibilities of high-pressure excursions due to pressure wave interactions as were observed in the JIP experiments. Fortunately the high-pressure excursions are usually short duration impulses, so still lie below the iso-damage curve. Intelligent coupling of loading and response tools, and more verification of the latter, would be worthwhile.

Water sprays are here to stay and the use of units having localised intelligence[45] is an interesting new development which might conceivably obviate false alarms and high retrofit costs. A new passive method for generating water sprays may if developed also permit retrofit and would obviate the need for gas trigger.

The series of "large tests" gave rise to many surprises. We assembled a large bank of important new data at a scale not tackled heretofore. Nevertheless, apart from revising CFD codes to give results more consistent with the experimental results, there has as yet been very little effort expended on detailed interpretation of the experimental findings. Paradoxically, we have created an enormous bank of data yet there is almost too much in any one experiment fully to assimilate at present. It may well be that effort expended on trying to understand *precisely* what was happening in any one given experimental test is ultimately more useful in nailing our understanding of the physics, and so improving predictability, than any of the global or average examination of the effects. In other words, we need now to turn our attentions to the underlying science to achieve a step change in both ability and confidence of predictions for such complex situations.

Just as prior to Piper Alpha, commercial considerations put a slight damper on wider and rapid know-how dissemination, so also now, publication embargoes by sponsoring organisations of 2 years or so are very common - and some modifications to CFD codes are also kept proprietary giving the latter a “black box” image. This must lead to inefficiency in restricting the useful “gearing” provided by the worldwide scientific community.

It is perhaps worthwhile to recall that our knowledge of the mechanism of flame acceleration, often known as the Schelkin mechanism, which is responsible for pressure generation in congested structures is due almost entirely to the Russian Gas Dynamicist Schelkin and the German chemist, Wagner. The experiments, which they conducted, were laboratory studies of flame propagation in rough tubes and spherical flame propagation though a series of grids. In other words one of the most important of all the building blocks of our current understanding was supplied by scientists working in quite different countries and with quite different aims.

There is likely to be little or no appetite for further research sponsorship by the offshore industry at the present time and the author sees no need for more giant tests at present. It seems very likely that if the new information which has been generated were even more widely known and widely available, that the world scientific community would be able to utilise it in may different ways. It is also likely that further improvements in our understanding would be so generated.

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