HAZARDARDOUS INSTALLATIONS DIRECTORATE

OFFSHORE DIVISION

FIRE AND EXPLOSION STRATEGY

ISSUE 1

CONTENTS

SUMMARY

The topics covered in this document are:

- source terms;
- ignition;
- fire and gas detection;
- dispersion and ventilation;
- fire and explosion hazard assessment;
- fire and explosion consequence assessment; and
- prevention, control and mitigation of fires and explosion.

The prioritisation of specific strategy topics is subject to continuous change and is not addressed in this document. Not all identified strategy issues will be carried forward at this time.

This document presents the strategy development carried out by HSE's Offshore Division (OSD) to address fire and explosion issues on offshore installations. It provides an overview of the current state of knowledge with regard to fire and explosion hazards, their prevention, control and mitigation. It identifies current areas of uncertainty and describes the strategy areas where areas of significant uncertainty require clarification.

INTRODUCTION

BACKGROUND

To support its statutory role in enforcing offshore health and safety legislation the HSE must maintain its position at the technical forefront of fire and explosion issues. This document presents the strategy areas identified developed by the Offshore Division to address fire and explosion issues on offshore installations. It summarises the current position with regard to knowledge of fire and explosion hazards and their mitigation, identifies areas of uncertainty and sets out the potential actions required to address significant areas of uncertainty. The prioritisation of specific strategy topics is subject to continuous change and is not addressed in this document. Not all identified strategy issues will be carried forward at this time.

OBJECTIVES AND SCOPE OF WORK

The overall objective of the document is to identify the areas which OSD has identified as requiring possible future work to address significant areas of uncertainty in fire and explosion issues on offshore installations.

The topics covered in this document are:

- source terms;
- ignition;
- fire and gas detection;
- dispersion and ventilation;
- fire and explosion hazard assessment;
- fire and explosion consequence assessment; and
- prevention, control and mitigation of fires and explosion.

The detailed scope of work is as follows:

(i) provide an introduction to each topic area, e.g. describing the scope of the review, the nature of the hazard etc (as appropriate to the topic area);

(ii) describe the significance of the topic with regard to the risk of major accidents on offshore installations;

(iii) summarise current knowledge of the topic (i.e. reference to completed and on-going research, standards, codes of practice, design guidance etc);

(iv) summarise existing modelling capabilities (as appropriate to the topic area);

(v) based on the results of (iii) and (iv) above, identify areas of uncertainty;

(vi) summarise current industry practice (i.e. reference to approaches taken in Safety Cases, extent of implementation of existing codes, guidance etc, awareness of issues);

(vii) summarise areas identified to potentially be carried forward as part of OSD 3's strategy development.

The prioritisation of specific strategy topics is subject to continuous change and is not addressed in this document.

SOURCE TERMS

BACKGROUND

This section is concerned with characterisation of the initial outflow of fluid following a loss of containment (discharge rate and exit condition), as well as the spread and evaporation of liquid pools and the near-source dispersion of jet releases.

Proper characterisation of the source term is an important element of hazard assessment. However it can be an onerous task due to the complex nature of releases which occur on offshore installations, i.e. high pressure, multi-phase, multi-component releases with depressurisation occurring through complex networks of pipework and vessels with the added complication of blowdown and/or isolation.

Hydrocarbon release statistics (OTO 99 079 and Pratt, 2001) show that gas leaks are the most common type of release (56% of all releases) with oil releases (16%) and non-process releases (11%) also significant. Pipework is the most significant leak source (61% of all leaks).

CURRENT POSITION

Discharge from vessels, pipelines and equipment

The prediction of single and two-phase release rates was reviewed in Phase I of the Joint Industry Project (JIP) on Blast and Fire Engineering for Topsides Structures (BFETS), work package G1(c). This study concluded that, whilst the idealised cases of single phase and single component, two-phase releases had been studied in detail, there was little information on the behaviour of the type of hydrocarbon mixtures likely to be found on offshore structures. The report (OTI 92 587) suggested that a modest experimental programme of releases involving representative hydrocarbon mixtures would be beneficial in understanding the flow regime for such releases and establishing a dataset upon which to further develop existing modelling techniques. The experimental programme was not been undertaken in subsequent phases of the JIP, therefore this uncertainty remains. Catastrophic releases (e.g. due to rupture of a vessel) are also a significant area of uncertainty, although are not a primary concern for offshore installations.

Near-source dispersion of high-momentum jet releases

Gas jet releases

Air entrainment into gas jets has been extensively studied and various models exist to predict the dispersion of unobstructed jets in the atmosphere (see below). Experimental work has been undertaken in the field of impinging releases but little of direct relevance to offshore installations (complex arrays of obstacles). The work of most relevance is that recently undertaken as part of the JIP on ‘Gas Build-up from

High Pressure Natural Gas Releases in Naturally-Ventilated Offshore Modules' (Cleaver et al, 1998, 1999), which included both free and impinging gas releases. Phase I of the BFETS JIP identified a lack of data for the under-expanded region of high pressure jet releases. This does not appear to have been addressed in subsequent phases of the JIP and therefore remains an uncertainty.

Flashing liquid releases

Various experimental programmes have been conducted since Phase I of the BFETS JIP to better characterise the release and near-field dispersion of flashing liquid jets and provide data for model development and validation, e.g. Barton and Moodie (1992), Allen (1996, 1998, 2000) and AIChE (1999). These experiments have included impinging releases, which represent the area of greatest outstanding uncertainty (concerning rain-out, ice formation and re-evaporation). Further experimental and modelling work is planned and in progress in this area.

Liquid pool spread and evaporation

Recent HSE-funded experimental work (Cleaver et al, 2001) has been undertaken to resolve uncertainties in the spreading behaviour of liquid spills over horizontal surfaces and to investigate pool spread within bunded areas of different shapes, including the potential for bund overtopping.

Investigation of the characteristics of spreading of unconfined oil pool fires on steel decks is underway.

MODELLING CAPABILITIES

Discharge from vessels, pipelines and equipment

A range of simple models are available to predict discharge rates from single vessels or pipework, covering single phase flow (gas or liquid), two-phase flow and pumped releases, as documented in references such as CMPT (1999) and Lees (1996). Improvements have been made, in particular, to the models and guidance now available for two-phase flow prediction.

Most of the above models treat multi-component mixtures as pseudo single component fluids with 'average' properties. Models are not yet available which incorporate rigorous multi-component thermodynamics, although an HSE-funded research project is currently in progress to develop such models (Topalis, 1999).

For the blowdown of, or accidental release from, pipelines, simple models are available, but sophisticated codes have also been developed to account for the complex thermodynamics, fluid mechanics and heat transfer processes occurring in multi-component, multi-phase flash and depressurisation (Richardson and Saville, 1995 and Mahgerefteh et al, 1999). The former model is equally applicable to depressurisation of networks of vessels and pipework.

Near-source dispersion of high-momentum jet releases

Gas jet releases

Various integral models are available to predict the dispersion of free (unobstructed) jets in the atmosphere, e.g. JINX (Advantica), AEROPLUME (Shell) and TECJET (DNV). Simple models have also recently been developed under HSE funding for obstructed jets (Lewis, 1998 and Cooper, 2001), although their validity for application to the highly congested environment of many offshore installations is uncertain.

Flashing liquid releases

As for gas jet releases, various integral models are available for free (unobstructed) two-phase jet dispersion, e.g. EJECT (HSE/AEA Technology) and RELEASE (AIChE, 1999), which make the simple assumption of homogeneous equilibrium flow. CFD has also successfully been applied to two-phase jet dispersion to allow for non-homogeneous, non-equilibrium conditions (Kelsey, 2000). Recent reviews of two-phase release and near-source dispersion have been undertaken on behalf of HSE (Ramsdale and Tickle, 2000 and Witlox and Bowen, 2002). Work is on-going by HSL to adapt the EJECT model to cover impinging two-phase jets.

Liquid pool spread and evaporation

Various integral models are available to cover evaporating as well as boiling pools, bunded and unbunded releases, instantaneous or continuous releases and spills on water as well as land. These models include GASP (HSE/AEA Technology), LSMS (CERC), LPOOL (Shell/Exxon). It is not known whether any or all of these models have been modified to take account of the most recent research undertaken on liquid spread over horizontal surfaces (referred to above).

INDUSTRY PRACTICE

Simple correlations or integral models form the basis of most evaluations of source terms in QRA studies of offshore installations, although the details of such modelling are rarely presented in Safety Cases. The key issues which have been identified are as follows:

- **Use of release rate ranges**. Offshore QRA studies, out of necessity, categorise releases into defined ranges in order to simplify the consequence modelling. This categorisation may be on the basis of mass release rate or hole size and may be different for gas or oil releases. The choice of release rate ranges is arbitrary but, as noted in CMPT (1999), the QRA results can be sensitive to this choice.

- **Calculation of release rates.** Most QRA studies appear to assume constant (ie time invariant) release rates. In reality the release rate will vary with time depending on such factors as depletion of the source inventory, successful operation of emergency isolation and/or blowdown and changes in the phase of the release. Well-validated models exist to simulate the transient release from a pipeline or network of connected vessels (e.g. Richardson and Saville, 1995) but are not commonly used in hazard assessment.

- **Selection of representative set of release scenarios.** The selection of the representative release scenarios for an installation is a vital step in QRA, yet is often not explained in sufficient detail in Safety Cases. Release scenarios should be 'representative' in respect of the magnitude of the release, its duration, location, orientation, the type of fluid released and the coverage of the various areas on an installation from which a major accident could emanate. Deficiencies in the selection of representative release scenarios have been found in recent Safety Cases. CMPT (1999) provides guidance on selection of failure cases but notes that this is arbitrary. With the increasing use of risk-based approaches to fire and explosion resistant design and assessment (e.g. BP, 2001), the adequacy of the representation of the full range of potential release scenarios on an installation is becoming increasingly important.

- **Treatment of multi-component thermodynamics.** As noted above, most hazard assessment calculations are undertaken on the basis of 'pseudo' single component behaviour. Codes such as those of Richardson and Saville (1995) and Magherefteh et al (1998) for analysis of blowdown (or accidental release from) networks of vessels and pipelines, which include rigorous multi-component thermodynamics, are not generally used.

- **Appreciation of uncertainties in source term.** Simplifications are a necessary part of source term evaluation for offshore installations due to the complex nature of the hydrocarbon releases which can occur. However, there appears to be no systematic appraisal by duty holders of the uncertainties associated with the various modelling simplifications and their overall impact on the hazard assessment. Without this, it is difficult make judgements as to appropriateness of the assumptions made. An appreciation of the relevant uncertainties is becoming more important with the increasing focus on 'realistic' gas cloud volumes, the evaluation of which may be critically dependent on the correct representation of the source characteristics.

STRATEGY DEVELOPMENT ISSUES

Near-source gas jet dispersion

Impinging releases

- In the congested environment of offshore installations impingement of gas jets on adjacent equipment or structures and interaction with background ventilation is likely and will be a significant factor determining gas dispersion. Simplified treatments of impinging gas jets have recently been developed but lack validation.

- CFD has been applied to large scale impinging gas jet releases as part of the recent JIP on 'Gas Build-up from High Pressure Natural Gas Releases in

Naturally-Ventilated Offshore Modules' but the detailed findings of this work are not yet available.

Under-expanded region

- There is also a lack of understanding of the behaviour of the near source (under-expanded) region of high pressure gas releases, which is presently overcome by defining a 'pseudo' source.

Two-phase jet dispersion

- Two-phase releases represent a significant, although not the predominant, fraction of offshore hydrocarbon releases (9%). A common source of error is in the assessment of two-phase flashing flow rates. This may introduce non-conservatisms if two-phase releases are assumed where liquid releases would in reality occur or gas releases are assumed where two-phase release may in fact occur. Current integral models of two-phase jet releases make simplifying assumptions (i.e. homogeneous equilibrium) and may be insufficiently validated.

- Numerical models have been successfully applied to two-phase jet dispersion but require further validation. Such models provide the basis for evaluation of flow features of practical interest, e.g. impingement and rain-out, which cannot currently be addressed (development work underway on former).

Multi-component fluid releases

- Phase I of the JIP suggested a modest experimental programme to characterise the release behaviour of the type of hydrocarbon mixtures found on offshore installations. This experimental programme appears not to have been performed in subsequent phases of the JIP.

- Most assessments of source terms in offshore QRA studies are based on pseudo single component behaviour which may be subject to significant uncertainty.

- More complex codes for vessel and pipeline blowdown (including accidental release) include rigorous multi-component thermodynamics, but do not appear to be used in hazard assessment work.

- Research is currently underway to incorporate multi-component thermodynamics in commonly used hazard assessment software.

Gas lift hazards

- Downhole annulus gas inventories may be of the order of several tonnes and represent a significant topsides fire and explosion hazard as they are outside the scope of protection of the blowdown system.

- Widely-varying assumptions are made about the nature of releases associated with gas lift systems and may even omit consideration of the potential for release of the downhole gas inventory.

Selection of representative set of release scenarios

- The selection of release scenarios is a vital step in QRA and is becoming increasingly important given the use of risk-based approaches to fire and explosion resistant design and assessment.

Uncertainties in source term evaluation

- Evaluation of source terms in hazard assessment studies of offshore installations invariably involves making simplifications and approximations.

- Examples include:

  - use of pre-defined release rate ranges (various approaches adopted);

  - assumption of constant release rates;

  - representation of multi-component releases as pseudo single component (as discussed above);

  - omission of consideration of impinging releases; and

  - simplified treatment of two-phase releases.

- An appreciation of the uncertainties in source term evaluation is becoming more important with the increasing focus on 'realistic' gas cloud volumes, the evaluation of which may be critically dependent on correct representation of the source characteristics.

- Advances continue to be made in the evaluation of source terms, covering such aspects as the modelling of impinging gas jet releases (simple models have now been developed), incorporation of multi-component thermodynamics into simple hazard assessment software (HSE-funded project in progress) and the modelling of two-phase releases (increasing guidance available for hazard assessment work).

IGNITION

BACKGROUND

Ignition causes a release of flammable liquid or gas to become a fire (jet fire, flash fire, pool fire etc.) or explosion. There are many possible sources of ignition and those that are most likely will depend on the release scenario. Sources of ignition include electrical sparks, static electricity, naked flames, hot surfaces, impact, friction, etc.

STRATEGY OBJECTIVES

For gas releases, the timing of any ignition is important in determining the risk and consequences. Early ignition will tend to give rise to a jet fire, whilst delayed ignition can cause an explosion or flash fire, depending on the degree of confinement, congestion, ventilation regime etc. Objectives in this area of fire assessment are:

- To identify areas of uncertainty in the characterisation of ignition sources;
- Identify where the uncertainty is significant in relation to ignition characteristics and offshore risk assessments;
- Initiate research to increase knowledge and understanding in ill-defined areas of ignition characterisation; and
- Promote the use of a consistent methodology in the use of realistic ignition source characterisation.

CURRENT KNOWLEDGE OF IGNITION HAZARDS AND MODELLING CAPABILITIES

Known ignition sources for vapour mixes

- Electric sparks and arcs (from electrical circuits, motors, switches etc.);
- Mechanical sparks (from friction and falling objects);
- Static electrical sparks;
- Lightning;
- Flame (including flaring, boilers, smoking);
- Hot surfaces (including hot work, hot processing equipment, electrical equipment);
- Heat of compression;

- Chemical reactions (e.g. auto-ignition of oil-soaked lagging on hot piping); and
- High energy radiation, microwaves, RF, etc.

Ignition of non-vapour mixes

There is little data available relating to ignition characteristics of:

Diesel Oil Mists - a dispersion of droplets with diameters <10 microns - such as might be produced when a saturated vapour condenses. It is significant because oil mists may be in a physical form that gives the lowest ignition energies.

Crude oil mists and crude oil-water mixtures - a significant number of UKNS reservoirs now produce high water cut fluids. Ignition of oil–water mixes are not well understood.

IGNITION PROBABILITY ESTIMATES & MODELLING

Ignition sources identification

The generation of ignition probabilities or development of sophisticated ignition probability models is highly dependent on available data.

Friction or the impact energy required to cause ignition - there is renewed interest in friction because of the ATEX Directive, which requires all mechanical equipment for use in flammable atmospheres to be classified in the same way as electrical equipment from 2003.

Ignition of high-pressure releases caused by electrostatic discharges occurring in, or as a result of the release. These events still occur and are very relevant where pipework exists which contains multiphase, high pressure fuels.

Uncertainties in data

Current available ignition data contains uncertainties, specifically:

(i) the leak duration, type and dimensions of module, ventilation rate and types of ignition sources;

(ii) the use of expert judgement in their development to compensate for lack of statistical data; and

(iii) lack of relevant statistical data for ignition model validation.

INDUSTRY PRACTICE IN ASSESSMENT OF IGNITION HAZARDS

Safety cases in general do not contain the level of detail for identifying individual ignition sources.

Hazardous area classification is presented as read and some information given about permit to work systems.

Different ignition probability models appear to be in use by different duty holders.

The Cox, Lees and Ang (1990) model, is used extensively even though Cox, Lees and Ang state that it was speculative only.

STRATEGY DEVELOPMENT ISSUES

An updated ignition probability model is being developed based on the latest OIR12 data.

- Disseminate the findings of the UKOOA / OSD ignition probability work;
- Actively support Phase II of the UKOOA project, which proposes a second phase to develop a platform-specific ignition model;
- Raise awareness of ignition sources within the industry since ignition probability is a fundamental input to fire and explosion QRA.

FIRE AND GAS DETECTION

BACKGROUND

There are two principal types of detector which are commonly in use in off-shore installations: heat, flame & smoke, and flammable gas instruments. The most significant for risk reduction are gas detection systems, since they give the earliest warning of hazardous situations. Infra Red (IR), line-of-sight or point type detectors which identify an accumulation of gas and acoustic leak detectors, are also used. The OSD strategy is to promote the use of a combination of sensors, thereby giving early leak detection with the acoustic detectors and identifying a gas cloud accumulation with the IR type sensors.

STRATEGY OBJECTIVES

Objectives in terms of effective gas detection revolve around the life cycle of the system:

- To specify performance requirements based on installation specific hazard scenarios;
- To identify where deficiencies exist with regard to detector specification and effective operation, including maintenance;
- Initiate research to increase knowledge and understanding in ill-defined areas of detection systems effectiveness; and
- Promote the use of a consistent methodology in the location of detectors, to maximise detector effectiveness.

CURRENT KNOWLEDGE OF DETECTION EFFECTIVENESS

Vapour state detector specification

The key requirements of the system are that it should (a) respond effectively and reliably to the hazard and (b) be tolerant of the environment and working procedures. This requires knowledge of the following:

(i) Real-time ventilation surveys are critical in detector performance. Re-circulation and/or dead zones need to be identified. This is rarely carried out, and is an OSD priority area of concern;

(ii) Detector head location and coverage should be specific to the hazard conditions within the installation area covered. Head location commonly follows a grid pattern;

(iii) Detector sensitivity to oil or mist releases is variable and there are large uncertainties with calibration systems. OSD regard the use of liquid leak detection as a future concept to be pursued;

(iv) Many gas detectors are sensitive to low (geometric) sunlight, fog / condensation and reflections. Newer models overcome this problem;

(v) Coverage by point detectors is sensitive to the ventilation regime. Beam instruments give wider coverage;

(vi) Point detectors can give a higher maintenance burden than Line of Sight Detectors;

(vii) An analysis of 8 years of data relating to hydrocarbon releases (HSE, 1999b) indicates that across all installations and detection systems an effective detection rate of about 60% has been recorded.

Liquid or droplet mixture detection specification

Oil mists are generated by the release of flammable liquids under pressure. Oil mists are very flammable and can ignite at a lower temperature than most hydrocarbon gases. Most oil mist detectors are optical beam devices. The current evidence is that gas detectors do not seem able to detect oil mist releases. Wormald & Shell have developed a mist detector for installation in ships engine rooms.

Fire and smoke detection

Fire may be detected by heat rise or flame sourced radiation in the UV, visible and IR spectrum ensuring that all types of fire will alert the detector system. Current knowledge is that these instrument systems are generally reliable and effective. They are independent of the ventilation regimes, unlike gas detectors.

Detector location

Fire detection

Various rules of thumb are used to determine the location and coverage of the different types of fire detector. Point heat detectors in open, naturally ventilated areas are sited at approximately a density of 1 per 25m^2 and at spacing of 7m with a maximum distance from bulkheads of 3.5 m. In enclosed mechanically ventilated modules, they are sited at approximately 1 per 37 m^2 and 9m apart with a maximum distance from bulkheads of 4.5m. They are not applied in areas with high ceilings above 8m (point heat detectors have poor sensitivity with height).

Flame detectors are sited such that their vision cone covers areas where fire may occur. For IR flame detectors around 15m is considered a reasonable range because of obscuration by smoke and lack of sensitivity at the periphery of their field of view. They are generally sited at the corners of an area or module. CAD tools are used to optimise their coverage at the design stage. Triple band IR systems are less prone to false alarms.

Point smoke detectors rely on the transport of combustion products (particulates and gases) to the detector by convection. The numbers of detectors can be reduced with increased ceiling height because of more uniform distribution, although the concentration will be less and the sensitivity of the detectors must be adequate. Current smoke detectors are located at not more that around 7.5m apart and are not appropriate for high ceilings (>10.5m).

Gas detection

Detector head spacing is governed by the size and geometry of the area (confinement and congestion), ventilation and the nature of the release. Typically the minimum spacing in congested areas is around 5m based. Problems can occur in large volumes or trapped volumes where there is local confinement that restricts the venting path. Gas/vapour tends to slump, particularly in low air movement areas, after a liquefied gas release because the local gas cloud is relatively dense and cold. Detector heads should be located in a 3D pattern with some heads at low level in modules that are liable to have gas vapour slumping.

Duct sampling. Either point or beam detectors can be installed in HVAC and other ductwork. Generally beam detectors are not an area of concern as they are more likely to provide coverage across the duct.

Acoustic detectors. Location is based on identifying the potential sources of leaks, e.g. all joining parts in high pressure gas installations. An ultrasound map of the background noise can be determined to decide the alarm level and assist with selection of the optimal location. Care must be taken to avoid acoustic reflections that may produce false alarms.

It is possible to use the detectors in a grid system as for the concentration-based detectors above. However, the location criteria are different and are not as well understood as for point catalytic/IR detectors because of their newness.

AREAS OF UNCERTAINTY

Guidelines for optimal combination of point, beam and acoustic detectors are dispersed in various documents and lack useable detail.

Conclusions from analysis of JIP data are not particularly useful for effective detector set-up, i.e. insufficient number of release scenarios to cover the conditions found in practice. Location of detectors for various types of flammable gas release: methane, propane and condensates are not defined.

There is sparse information on effectiveness of gas detectors to detect low rate releases (<1.0 kg s^{-1}) but which may become significant over a period.

Response of instruments calibrated for methane to higher chain hydrocarbons are not well defined and awareness in the Industry is low (methane and C5-C8 hydrocarbons)

Relation of measurement parameters of beam (%LEL.m) and acoustic (dB) to flammable hazard (e.g. explosive cloud volume) is not well understood.

Application of intelligent data processing to assist in better detection of fire/gas incidents is not used offshore, i.e. pattern recognition technology. It is an area of potential benefit.

INDUSTRY PRACTICE

Industry practice is based on the general guidance provided in the UKOOA guidelines (UKOOA, 1995) that is then translated into more specific rules and guidance in company codes of practice (e.g. Shell, 1995 and BP, 1997). BS EN ISO 13702 contains high level advice on detection systems.

A JIP of large scale experimental study of gas build-up from high pressure releases in naturally ventilated offshore modules was completed in 2000. This JIP study did not address detection directly, however the data is being used for evaluation of the effectiveness and optimisation of gas detection networks.

The principal factors explored in the tests were release rate, direction and location, module wall configurations, and wind speed and direction (both external and internal). The main findings were:

(i) The use of a grid based on 5 m spacing for point detectors was successful in detecting releases where clouds formed within the module;

(ii) When only small clouds formed, or cloud growth was slow, detection times increased and in some cases the releases were not detected at all;

(iii) Halving the spacing between detectors slightly reduced detection times but at the expense of a large increase in the number of detectors required. Doubling the detector spacing caused a large increase in detection times;

(iv) The IR point detectors performed better than the catalytic detectors, both in the number of releases detected and in the detection time;

(v) The IR beam detectors showed good performance in the initial configuration and when comparing their performance to rows of IR point detectors; and

(vi) Well-placed detectors can improve the performance of a detection system and this emphasises the need for knowledge of dispersion, the processes being undertaken in a module, and the equipment layout when deciding detector placement.

STRATEGY DEVELOPMENT ISSUES

(i) Further, more specific guidance is needed on the most effective location of detectors in a system. This guidance should be based on experimental studies (e.g. JIP) of:

- Methane releases;
- Higher fraction, e.g. propane, releases; and
- Condensates (C5-C8 hydrocarbon) releases.

(ii) The response of sensors calibrated to one type of hydrocarbon when exposed to longer or shorter chain hydrocarbons specific to the well fluids should be investigated with the aim of improving overall detection performance.

(iii) In assessment and inspection the duty holder should be made aware of real time ventilation data as a key element in installing an effective gas (and smoke) detector system.

(iv) The integral use of acoustic leak detectors and IR systems needs to be studied and guidance developed from the findings.

DISPERSION AND VENTILATION

BACKGROUND

This section covers:

- dispersion of flammable or toxic gases or vapours;
- dispersion within a module, over an installation, over the sea-surface, and sub-sea;
- dispersion of releases which are passive, momentum-dominated or buoyancy-driven;
- ventilation of open, sheltered or enclosed areas, primarily as a means of minimising gas build-up and aiding dispersion;
- forced or natural ventilation; and
- ingress of smoke into the TR.

Dispersion and ventilation are recognised as key topics in the control of fire and explosion hazards on offshore installations. They have been the subject of various research studies over the past 10 years and are the subject of increasingly detailed modelling by duty holders as a means of demonstrating lower risk levels.

STRATEGY OBJECTIVES

(i) identify areas of uncertainty in evaluation of ventilation and dispersion.

(ii) promote the use of consistent methodologies in the evaluation of installations ventilation and dispersion analysis,

(iii) Initiate research to increase knowledge and understanding of ventilation and dispersion analyses,

KNOWLEDGE OF DISPERSION AND VENTILATION

Standards, guidance and codes of practice on ventilation

The standards, guidance and codes of practice relevant to ventilation on offshore installations include BS 5925, ISO15138, BS EN60079-10, IP 15, API 500 and NORSOK H-001. A review of these documents has highlighted a number of areas of concern:

- there is a lack of consistency between the various standards which apply to ventilation and dispersion in offshore modules. In particular, the criteria against which the adequacy of ventilation can be assessed are inconsistent, with some standards using air change rates as the key criteria, whilst others use ventilation rates;

- the validity of the performance criteria in current standards is uncertain. In particular, measures related to air change rate are of doubtful validity, as this measure gives no indication of air distribution and is extremely difficult, if not impossible, to quantify in practice;

- the specification of 12 air changes per hour as representing adequate ventilation in naturally-ventilated modules (IP15, API RP500) lacks a sound basis; and

- the applicability of the current standards is unclear:

  - the maximum leak size which is effectively dispersed by the recommended ventilation rates is not clear;

  - no account is taken of the influence of the leak on local ventilation conditions;

  - basing the definition of 'open' areas on wind speeds may not be the best measure; and

  - if wind speeds are to be used to define open areas, the existing guidance should make it clear what location the speeds are referred to.

Research on gas dispersion

Notable research studies on dispersion on offshore installations include:

- Phase 1 of the BFETS JIP (Report OTI 92 591) the main conclusion of which was that, whilst much of the phenomena of gas releases is understood, there is much uncertainty in the way that these phenomena would interact in real offshore scenarios;

- JIP on 'Gas Build-Up from High Pressure Natural Gas Releases in Naturally Ventilated Offshore Modules' (Cleaver et al, 1998 and 1999), involving gas dispersion trials in the large scale test rig at Spadeadam. This project also included a CFD model evaluation exercise (showing good qualitative agreement) and development of a workbook approach for flammable gas cloud prediction;

- A study by Saunders et al (2001) involving on-site measurements and CFD modelling to determine the adequacy of natural ventilation on offshore installations; and

- On-going work by HSL to review test methods for smoke/fire HVAC dampers.

MODELLING AND MEASUREMENT CAPABILITIES

Dispersion models

Gas dispersion

There are a number of areas of uncertainty with regard to the modelling of offshore ventilation and dispersion:

- It would appear that models for predicting the size and composition of gas clouds which could form in congested confined modules, have not been extensively validated. This is in part to a lack of reliable experimental data, which is now available (Cleaver et al, 1998, 1999);

- Models developed prior to the recent JIP data (Cleaver et al, 1998, 1999) should be validated against that data;

- The main CFD model validation activity has only recently been published (Savvides et al, 2001a, b). The performance of two CFD codes; FLUENT and FLACS is claimed to be good when compared with large scale data, however the details of the validation exercise are not yet available;

- An integrated CFD-based approach to the modelling of ventilation, gas dispersion and explosion simulation has become more commonplace. It is highly likely that compromises are being made in this approach, but the uncertainties have not yet been addressed;

- The competency of those using CFD models is a key issue, but there is no ‘best practice guidance’ available for offshore applications;

- The validity of models for ventilation and dispersion in congested confined modules in cases where the wind speed is low, is uncertain.

Measurement capabilities

Measurement of ventilation rates in enclosed, mechanically-ventilated areas is relatively straightforward and well documented. Measurement of ventilation rates in relatively open conditions is much more difficult and depends on the flow regime. Under plug flow conditions air speed measurements or tracer gas techniques can be employed. The data would then have to be correlated with wind speed and direction. This approach can, however, be invalidated where ‘short circuiting’ of the air flow occurs. Smoke releases or point measurements of air velocity on a deck can highlight areas of recirculation or low wind speed, but do not provide any information on ventilation rate.

INDUSTRY PRACTICE

Wind tunnel modelling and a range of mathematical modelling techniques are often used to evaluate offshore air movement and dispersion. In a sample of recent Safety Cases only one provided validation of modelling against offshore experimental measurements, as required by ISO 15138.

STRATEGY DEVELOPMENT ISSUES

Standards and guidance

- The current standards, guidance and codes of practice are inconsistent, in some cases lack validity, and their applicability is uncertain.

- There is a need to re-examine the basis of current standards and guidance, with a view to defining more appropriate and practical measures of performance.

- Establish, in consultation with industry. The feasibility of drafting best practice guidelines for the application of CFD and other approaches (eg workbook approach) to the prediction of offshore ventilation, dispersion, and gas build-up, particularly with respect to the effectiveness of gas and leak detection systems.

Models

- A recent JIP has provided much-needed data on gas cloud build-up in offshore modules (Cleaver et al, 1998, 1999; Savvides et al 2001 (a), (b)). Although a total of 66 tests were undertaken only two of these were at wind speeds of less than 1.5 m/s. Empirical models which have been devised using this data (Cleaver & Britter, 2001) could give misleading results if applied outside their range of applicability, for example in conditions of low wind speed. The performance of more advanced modelling approaches, such as CFD, is also uncertain for conditions outside those investigated in this JIP

- It is not clear whether models developed prior to the recent JIP data (Cleaver et al, 1998, 1999), such as CHAOS, have now been validated against that data.

- CFD is being increasingly used to predict gas dispersion and build-up, prior to explosion simulations. It appears that a range of modelling approaches are being employed, for example coarse grid simulations in one case (Holen, 2001), through to the use of half to one million grid cells in another (Savvides et al, 2001 (b)). Best practice has, it seems, not been established or agreed. Neither has the sensitivity of predictions of gas cloud size to the

CFD modelling approaches typically being employed by industry been established.

Dispersion calculations in exceedance modelling approaches

- A range of predictive techniques are being employed to calculate gas build-up and dispersion in exceedance modelling approaches. Since explosion over-pressure is related to gas cloud composition and size, it is important to understand that uncertainties in methods used to predict offshore ventilation and dispersion will ultimately be reflected in calculated exceedance curves.

- Guidance is need on the number of data points required to obtain statistical validity of an exceedance curve, and the methods used to interpolate and extrapolate from limited data points. In particular the validity of the "frozen cloud" and "symmetry" approximations used to extrapolate from a few hundred CFD simulations need examination.

- Develop and demonstrate practical guidance against which dispersion and ventilation of naturally ventilated modules can be designed and assessed.

POOL FIRES

BACKGROUND

A pool fire is a turbulent diffusion fire burning above a horizontal pool of vaporising hydrocarbon fuel where the fuel has zero or low initial momentum. Fires in the open will be well ventilated (fuel-controlled), but fires within enclosures may become under-ventilated (ventilation-controlled). Pool fires may be static (e.g. where the pool is contained) or ‘running’ fires. Pool fires represent a significant element of the risk associated with major accidents on offshore installations, particularly for Northern North Sea (NNS) installations that may have large liquid hydrocarbon inventories.

STRATEGY OBJECTIVES

The objectives of this area of fire hazard assessment are:

- Identification of areas of uncertainty in the characterisation of pool fires;
- To identify where deficiencies exist with regard to hazard description and effective mitigation measures;
- Initiate research to increase knowledge and understanding in ill-defined areas of hazard definition; and
- Promote the use of a consistent methodology in the accurate assessment of the risks posed by pool fires.

CURRENT KNOWLEDGE OF POOL FIRE HAZARDS

There are major uncertainties in the behaviour and properties of fires of condensate and higher molecular weight and multi-component materials and very large flames of all materials; behaviour of running fires and of liquids released from pressurised containment

The influence of water deluge and foam on fuel distribution and pool fire mass burning rates and the influence of pool shape on radiation and soot shielding is not well understood.

The effect of scale on fire size, geometry and radiation, particularly for very large fires and the ability to predict the overall behaviour of large hydrocarbon pool fires in offshore structures is poor.

Validation and accuracy of field model applications to offshore compartment fires is questionable.

There is no difference in the burning rate between pool fires on water or steel.

Fuel-controlled pool fires are characterised by rapid rise in temperature (up to 1300°C) and high heat fluxes (up to 320 kW m^{-2}) in insulated compartments.

The burning rate (kg s^{-1} m^{-2}) is not dependent on pool area at large scale and ignition criteria for external flames.

Pool spread characteristics of pool fires on steel plates are not well understood.

POOL FIRE MODELLING

Fire model evaluation in the Joint Industry Project

Phase I of the JIP (OTI 92 596/597/598) included a review of open hydrocarbon pool fire models. Three types of model were evaluated: semi-empirical models (e.g. WHAZAN), field models (e.g. CFD models) and integral models (falling between semi-empirical and field models). It was concluded that well-validated, semi-empirical models represented the best available models for the prediction of heat fluxes to objects outside flames, provided that such models are used within their range of validity.

Compartment fire modelling, have two types of Code: zone models and field models. It was concluded that zone models (typically used for modelling fires within buildings) encounter severe limitations in modelling large offshore compartment fires.

Phase II of the JIP included a fire model evaluation exercise. This considered three jet-fire scenarios, but no pool-fire scenarios. However it did generate high quality data that were considered suitable for future pool fire model evaluation. It has been recognised from Phase II of the JIP that a more extensive fire model evaluation exercise is warranted, involving a greater number of models and test scenarios.

Current status of pool fire modelling

POOLFIRE6 (Rew and Hulbert, 1996), sponsored by HSE has been validated against a wide range of test data and found to give good results for all fuel types except methanol. The model performs as well for smoky, obscured heavy hydrocarbon fuels as it does for clean burning fuels such as LNG. Other pool fire models widely used include that of Mudan and Croce (SFPE, 1995) and the pool fire models contained in Shell’s FRED software, DNV’s PHAST and NEPTUNE software packages and the ‘Yellow’ Book (and associated software, EFFECTS).

AREAS OF UNCERTAINTY

Ventilation-controlled pool fires

Prediction of burning rate

There is currently no reliable, general method for calculating ventilation-controlled compartment burning rates, and how they respond to changes in enclosure geometry, ventilation and fuel spill size. Without this basic knowledge of the rate of fuel consumption it is impossible to assess the internal temperature and size of external projected flame.

Extinction criteria

Currently no criteria have been established to determine when pool fires in compartments self-extinguish. Some preliminary data on this were produced by HSL (Atkinson, 2001) for fires in fully welded compartments. These tests also showed that relatively small cracks in key locations could prevent self-extinction.

External flaming

The large external flames projected from ventilation-controlled fires can threaten escape routes on offshore installations and a reliable method to assess the size and shape of external flames is needed. The key variable in such an assessment is the mass flow of unburned fuel from the fire. Computational methods might provide useful support to experimental work in this area.

Release of unburnt fuel vapour

External flaming may not occur if the burning hydrocarbon spill is sufficiently distant from the vent and there is no piloting at the vent. In this case unburned fuel vapour is released. The potential for the generation of explosive mixtures remote from ventilation controlled offshore fires should be investigated.

INDUSTRY PRACTICE IN ASSESSMENT OF POOL FIRE HAZARDS

Software packages commonly used for offshore QRA studies include codes such as ARAMAS, NEPTUNE and PLATO. These codes appear only to model open pool fires, which would not represent the particular features of confined or ventilation-controlled fires (e.g. external flaming).

STRATEGY DEVELOPMENT ISSUES

- To raise the awareness of the particular hazards posed by ventilation-controlled pool fires;
- To define the circumstances in which ventilation-controlled pool fires could occur on offshore installations;
- To develop simple tools to assess the hazards posed by ventilation-controlled pool fires;
- Specific note should be made when assessing hazards that include confined fires; is spread of a flame across the ceiling of a module and is there a potential for external flaming?;
- To develop an understanding of the current capability to model confined (fuel-controlled) pool fires;
- To evaluate such models against suitable large scale test data;
- To develop simple tools to assess the hazards posed by confined pool fires;
- To evaluate the pool spread characteristics of fires on steel plates.

JET FIRES

BACKGROUND

A jet or spray fire is a turbulent diffusion flame resulting from the combustion of a fuel continuously released with some significant momentum in a particular direction or directions. Jet fires can arise from releases of gaseous, flashing liquid (two phase) and pure liquid inventories.

Jet fires represent a significant element of the risk associated with major accidents on offshore installations. The high heat fluxes to impinged or engulfed objects can lead to structural failure or vessel/pipework failure and possible further escalation. The rapid development of a jet fire has important consequences for control and isolation strategies.

The properties of jet fires depend on the fuel composition, release conditions, release rate, release geometry, direction and ambient wind conditions. Low velocity two-phase releases of condensate material can produce lazy, wind affected buoyant, sooty and highly radiative flames similar to pool fires. Sonic releases of natural gas can produce relatively high velocity fires that are much less buoyant, less sooty and hence less radiative.

STRATEGY OBJECTIVES

- To identify areas of uncertainty in the characterisation of jet fires;
- Identify where the jet fire hazard is significant in relation to other hydrocarbon hazards;
- Initiate research to increase knowledge and understanding in ill-defined areas of jet fire evaluation; and
- Promote the use of a consistent methodology for evaluation of jet fire hazards.

CURRENT KNOWLEDGE OF JET FIRE HAZARDS

The hazards, characteristics and physical properties of hydrocarbon jet fires have been appraised in the Phase 1 reports of the Joint Industry Project on 'Blast and Fire Engineering of Topside Structures' (OTI 92 596/597/598). The main source of detailed information on the characteristics of jet fires covered in the reports on the programme of jet-fire research co-funded by the European Community. This programme studied single fuel natural gas and propane jet fires (Bennett et al, 1990).

Notable recent gains in knowledge have been in the area of unconfined crude oil jet fires and confined jet fires (compartment fires). These areas have been studied in Phase 2 of the JIP on ‘Blast and Fire Engineering of Topside Structures’ (Selby and Burgan, 1998) and another JIP on releases of ‘live’ crude oil containing dissolved gas and water.

Unconfined two-phase crude oil jet fires

Phase 2 JIP focussed on horizontal free jet fires of stabilised light crude oil and mixtures of stabilised light crude oil with natural gas viz:

- The free flame releases, of crude oil only, were not able to sustain a stable flame and one of the mixed fuel releases was also unstable.
- All the flames were particularly luminous compared with purely gaseous jet flames and generated large quantities of thick black smoke, mainly towards the tail of the flame.
- All the flames were highly radiative, with maximum time averaged surface emissive powers (SEP’s) ranging between 200 kW m^{-2} to 400 kW m^{-2}.
- The incident total heat fluxes (radiative and convective) measured on the pipe target were significantly higher for the mixed fuel tests than for the crude oil only tests, by a factor two in many cases. Typical values were in the range 50 kW m^{-2} to 400 kW m^{-2}.

Gosse, 1999 carried out a separate JIP to quantify the hazards posed by realistic releases of ‘live’ crude oil containing dissolved gas and water.

Small amounts of water had little effect on the characteristics of the fire, larger amounts produced a dramatic reduction in the smoke produced and increasing the water further took the flame to the point of extinguishment.

For high water-cut releases, smoke will be less of a hazard, but very high water-cut releases will not produce stable jet fires.

Confined fires

Work by Chamberlain (Chamberlain 1994 & 1995, OTO 94 011-024) and the Phase 2 JIP (Selby and Burgan, 1998), studied the effect of varying a range of parameters on the fire behaviour. Including size and location of openings (vents), fuel type, release height and pressure for jet fires. Gas temperatures within the compartment, wall temperatures, ceiling temperatures, target temperatures, heat fluxes to the walls, ceiling and target, gas composition of the smoke layer and fuel release rates.

JET FIRE MODELLING

Unconfined fires

It was generally accepted in 1991 that the semi-empirical models provided the most accurate and reliable predictions of the physical hazards associated with fires, providing their application is limited to the validation range of the model. (recorded in OTI 92 596) This conclusion essentially remains valid today. A recent CFD study, carried out for HSE/OSD (OTO 1999 011) by Shell, showed good agreement with medium and large-scale jet-fire experiments.

At present, commercially available semi-empirical models can provide accurate prediction of flame shape, flame size and external radiation flux to external objects but not heat fluxes to impinged objects. The latter must be treated empirically.

Confined jet fires

The general level of understanding of compartment fire behaviour is now sufficiently good to assess most compartment fire hazards with some confidence for modules having simple geometries. In particular jet-fire temperatures, smoke layer temperatures, heat fluxes to surfaces within the module, the extent of external flaming and internal impingement zones can be reasonably well predicted. Estimates for CO concentrations in the smoke layer are also available based on empirical relationships to temperature and flame stoichiometry.

AREAS OF UNCERTAINTY

Confined and Unconfined jet fires

Future improvement in model development of confined jet fires should focus on evaluating the combustion product emissions from module vents.

As fields reach maturity, increasing amounts of water are entrained and formation of an unstable jet fire my result. In unconfined jet fires the flame may be extinguished before the fuel supply has been cut off resulting in an explosion.

There is little information relating to high water cut (e.g. 3:1 or 4:1) releases.

Actual heat transfer from the fire to the vessel is not fully definable, and hence failure conditions and emergency depressurising requirements become uncertain.

INDUSTRY PRACTICE IN ASSESSMENT OF JET FIRE HAZARDS

Current industry practice is to analyse jet fires for length of the jet fire with respect to distances of plant equipment, buildings, population etc. The extent of impingement into affected area is considered along with the need for PFP, emergency depressurisation and other mitigation options.

It is assumed that personnel are able to survive and escape from exposure to heat fluxes less than 5 kW m^{-2}, but fatality is assumed for higher heat flux values.

The effect of jet fires with high heat fluxes (e.g. flame temperature of 1350 °C, heat flux of 400 kW m^{-2} are not generally taken into account in safety case assessments. This is because these types of flame are not included in current guidance.

STRATEGY DEVELOPMENT ISSUES

- To raise awareness of the effect of jet fires on pressurised systems and the inadequacy of API 521 for fire attack scenarios and the potential for under-sizing of pressure relief systems;
- To raise the awareness of the particular hazards posed by ventilation-controlled jet fires;
- To consider mitigation and control issues relating to the jet fires in the open and confined areas;
- To define the circumstances in which ventilation-controlled jet fires could occur on offshore installations;
- To develop simple tools to assess the hazards posed by ventilation-controlled jet fires;
- To collect data and understanding on the heat flux from high temperature jet flames (ca. 1350°C) and the effects of exposure on pressurised storage vessels;
- To develop an understanding of the current capability to model confined (fuel-controlled) jet fires;
- To evaluate such models against suitable large scale test data;

- To develop simple tools to assess the hazards posed by confined jet fires.

FLASH FIRES AND FIREBALLS

BACKGROUND

Accidental releases of flammable liquids or gases often result in the formation of a cloud of vapour that is dense relative to ambient conditions. If the cloud encounters an ignition source then a vapour cloud fire (VCF) may result. In the present context, VCF is taken to mean either a flash fire or a fireball. VCF's are important for two reasons:

- An intrinsic hazard, in the form of thermal radiation, assuming no or limited confinement/congestion, so that overpressures are not important.

- The possibility of escalation. It is highly likely that secondary fires may be started as a result of the flash fire / fireball and, there is a high probability that following a VCF there will be a steady fire, typically either a pool fire or jet fire (or a combination of the two).

STRATEGY OBJECTIVES

- To identify areas of uncertainty in the characterisation of flash fires and fireballs;

- Identify where the fire hazard is significant in relation to other hydrocarbon hazards;

- Initiate research to increase knowledge and understanding in ill-defined areas of flash fire and fireball evaluation; and

- Promote the use of a consistent methodology for evaluation of fire hazards.

CURRENT KNOWLEDGE OF HAZARDS

An overview of the incidents, experimental data and the methods for estimating the characteristics of vapour is given in the 'Guidelines for Evaluating the Characteristics of Vapour Cloud Explosions, Flash Fires and BLEVEs' published (1994) by the Centre for Chemical Process Safety. Since 1994, HSE has been involved in two experimental projects relating to fireballs and flash fires.

Fireballs/BLEVEs

The resulting size and shape of the fireball following the BLEVE failure of a vessel was dependent on the amount of fuel in the vessel and the mode of failure.

The resulting external radiation field and hence received dosage are dependent on fuel mass, wind speed and direction.

The duration of the fireball was seen to be dependent on the mass of fuel involved.

Surface emissive power is highest for the smallest release, because a smaller mass is superheated such that, it flashes to vapour most rapidly, producing a highly radiative flame.

The resultant fireballs gave their maximum power output before the fireballs reached their maximum volume and close to the lift off time.

Flash fires

Additional experimental work on flash fires was performed as part of a Joint Industry Project (CERC, 2001). Butler and Royle (2001) characterised the flash fires from turbulent, two-phase jet releases of propane (up to 4.9 kg s^{-1}).

The presence of obstructions in the path of the vapour cloud was found to alter the concentration of LPG vapour in the cloud dramatically with, in this case, significant decreases in the vapour concentration downwind of the fence. The concentration of gas in the vapour clouds formed was generally low and the vapour cloud fires produced were relatively lean. The flames were therefore often invisible. Ignition of the cloud was observed at concentrations below the Lower Flammability Limit (LFL) of 2.2 vol.%. This is thought to be due to localised pockets of high concentration of gas at locations where the average concentration is measured as being below the LFL. In some cases, the cloud was ignited, but the flame did not propagate throughout the cloud, resulting in the formation of isolated pockets of ignition. In no cases were fireballs observed.

MODELLING CAPABILITIES

Fireballs

The characteristics of fireballs (diameter, height, lift off, duration) are usually modelled using empirical formula based on the mass of fuel released. The far field thermal radiation is usually estimated by a:

- **Point source model,** where it is assumed that a certain fraction (usually between 0.25 and 0.4) of the heat of combustion is radiated in all directions; or

- a **solid-flame model** where the radiation received is calculated from the surface emissive power of the flames, the relative geometry of the target and fireball and the atmospheric attenuation.

Both types of modelling have their disadvantages. A point source model tends to overestimate the irradiance at distances below 5 fireball diameters and, for a solid flame model, the result obtained is very dependent on how the surface emissive power is defined and measured.

Vapour cloud fires

Vapour cloud fire models were review by Rew et al. (1995, 1996). The simplest form of vapour cloud model uses a gas dispersion model to define the flammable region and assumes that anyone in the flammable region will be killed. As part of the vapour cloud fire model (CERC, 2001), three models were analysed:

- Raj & Emmons (CCPS, 1994);
- CLOUDF (Cracknell and Carsley, 1997); and
- HSE Flash Fire, HSEFF (WS Atkins, 2000).

AREAS OF UNCERTAINTY

The conclusions from the CERC (2001) model assessment exercise were that, the application of models was limited to low momentum sources, there was little or no validation, and there were areas of disagreement in calculation of flame height and flame speed.

INDUSTRY PRACTICE IN ASSESSMENT OF HAZARDS

Vapour cloud fires are generally not considered off-shore as part of the safety assessment, unless the possibility of developing into a vapour cloud explosion exists.

STRATEGY DEVELOPMENT ISSUES

- To develop simple models to predict the occurrence and effect of vapour cloud fires.
- To develop a greater understanding of the effect of flash fires on personnel.
- To increase awareness of where the flash fire encroaches on evacuation routes.

- To more fully define fireball hazards in close proximity of process equipment.

- To develop a methodology to identify scenarios where a flash fire develops into a vapour cloud explosion.

- To develop an understanding of the current capabilities of models to address fireballs and flash fires and to predict the consequences of each.

EXPLOSION HAZARD ASSESSMENT

BACKGROUND

A wide variety of types of explosion may occur on offshore installations. These include unconfined explosions (overpressure generated by presence of obstacles), confined explosions (overpressure generated through a combination of confinement and obstacles), external explosions (a phenomenon associated with confined, vented explosions), internal explosions (e.g. within a flare stack), physical explosions (e.g. a failing pressure vessel), solid phase explosions (e.g. associated with use of well completion explosives), mist explosions and BLEVEs.

Explosions represent a significant component of the topsides fire and explosion risk on most installations. Over the 25 year period 1973-97 there were 10 significant (> 0.2 bar) explosions on offshore installations in the North Sea, 8 of which occurred in the UK sector, most during the 1980s (Vinnem, 1998). More recent data for the period 1992-99 shows that there have been 10 explosion incidents on UK installations, most internal explosions associated with gas turbines or flare systems.

CURRENT POSITION

Large Scale Experimental Data

There is now a considerable body of experimental data from large-scale tests that has greatly improved our understanding of how gas explosions behave in offshore installations. New phenomena have been observed which were not predictable by the models available at the time, for example the significant enhancement of the explosion pressure by the small-scale obstacles. In many cases, however, no in-depth analysis of the results has been undertaken and as a result the opportunity to gain even further insight into the explosion mechanism remains. Data from the large scale test is largely confined to measurements of overpressure and flame arrival time, however more detailed information (e.g. on flame speeds) is required for rigorous model evaluation and development.

Realistic Release Cases

The large-scale tests undertaken in Phase 2 and 3a of the JIP were concerned with quiescent, stoichiometric clouds filling the entire volume of the module. However there remains a question as to whether a realistic release, involving significant turbulence, could give rise to greater explosions overpressures than those observed in the tests. Phase 3b of the JIP addressed realistic release cases and the initial findings from this indicate that in some cases rapid filling of the module could occur with gas at near-stoichiometric concentrations. While lower overpressures generally occurred in the realistic release tests uncertainty still remains concerning whether this is always the case.

Mist Explosions

For equipment containing volatile liquids at elevated pressure, two-phase or ‘mist’ releases are possible. There has been limited experimental study of mist explosions and the mechanisms operating in mist explosions remain poorly understood. Because of the difficulty in characterising the initial conditions, their study is also experimentally challenging. In particular there is uncertainty in whether mists for certain drop sizes could generate explosions more violent than that of an equivalent vapour concentration.

MODELLING CAPABILITIES

The explosion models currently available may be categorised as follows:

- empirical models (e.g. TNO Multi-Energy model, Baker-Strehlow method, Congestion Assessment Method COMEX/NVBANG);
- phenomenological models (e.g. SCOPE and CLICHE); and
- CFD models (e.g. FLACS, EXSIM, AUTOREAGAS, CFX, COBRA and various research codes).

A critical review of modelling and suggestions for future areas of research and development up to 2000 is given in HSE (2004).

The empirical models have a limited range of applicability, cannot deal with complex geometries and have simplified the physics considerably. Nevertheless, these methods are useful for quick order-of-magnitude calculations and for screening of scenarios warranting further investigation with more sophisticated tools.

The phenomenological models are slightly more complex than the empirical models. They have a less limited range of applicability than empirical models, are essentially fits to experimental data and have a lower level of uncertainty than empirical models. They do not attempt to model the actual scenario geometry but instead represent it in a simplified manner, e.g. as boxes connected by corridors. The models are relatively easy to use, with modest computational requirements and therefore are suitable for use where large numbers of calculation runs must be made, as in exceedance curve generation.

CFD models can be divided into two groups; simple and advanced models. The distinction between the two groups, albeit somewhat arbitrary, is that the advanced models will attempt a more complete description of the physical and chemical processes involved, including better representation of the geometry and the accuracy of numerical schemes. To illustrate this difference, consider one of the key findings of Phase 2 of the JIP, i.e. the importance of taking into account small scale obstacles. The simple CFD models make use of porosity/distributed resistance (PDR) models in order to avoid having to resolve the smaller scales obstacles, while the advanced CFD models attempt the resolve the objects using adaptive mesh refinement. Compared to the phenomenological and empirical models, CFD offers the prospect of greater accuracy and flexibility, however computational run times are long and the scope for errors is greater. Particular areas of uncertainty are:

- Representation of geometry (as noted above).
- Modelling of combustion process. Commercial CFD codes use simple correlations derived from experiments without attempting to model the detailed combustion kinetics.
- Modelling of fluid flow. The turbulence model most often used in CFD explosion codes is not strictly applicable to high speed combusting flows.
- Application in overpressure exceedance calculations. This may involve:
    - the use of the same CFD code for both dispersion and explosion calculations (each having different modelling requirements);
    - Long run times prevent a sufficient number of separate CFD simulations (with associated concerns as to the quality of each simulation) to be carried out to make results statistically meaningful;
    - The application of uncertain ‘symmetry arguments’ or ‘physical reasoning’ to generate the cloud shapes and overpressure data for all the various leak scenarios of interest.
    - Uncertainties associated with the generation of ‘equivalent stoichiometric clouds’ within some CFD models can offset any gains in accuracy arising from sophisticated gas dispersion modelling and explosion overpressure calculation.
- **Validation and verification.** There has been a lack of disclosure of validation data for some codes. This issue of auditability is of particular concern where codes are being regularly updated and new versions issued on a regular basis.

INDUSTRY PRACTICE

Explosion hazard assessments undertaken for offshore installations may vary widely from simple assessments using empirical models to complex analyses using multiple CFD simulations. Key issues identified from a review of industry practice in this area are as follows:

- Explosion hazard assessments are sometimes undertaken in detail for some installations then by 'difference' for others. This raises questions as to whether the installations in question are indeed comparable from an explosion hazard perspective.

- A common assumption made is that if the explosion analysis is undertaken on the basis of a module filled entirely with gas at stoichiometric composition that this must represent the worst case. This neglects the important influence of:

    - congestion in determining localised peak overpressures and that the turbulence associated with a realistic release case may give more severe overpressures (even if the gas does not completely fill the module);

    - in calculating explosion risks in relation to escalation and TR impairment, calculation of low frequency worst case explosions will potentially ignore higher frequency, lower overpressure incidents that are capable of significantly contributing to the overall explosion risk.

- In assessing realistic release cases, duty holders may assume that explosion overpressures scale in a simple manner with gas cloud volume, but this again neglects the important influence of congestion.

- The methodologies used for the development of exceedance across the industry curves are not consistent. The treatment of uncertainties is not clear and the wide range of methodologies employed, ranging from use of generic curves, combinations of phenomenological and CFD modelling and solely CFD modelling, prevents comparison between approaches used.

- The development of exceedance curve approaches for gas explosion modelling does not appear to be systematically documented or auditable.

- For explosion analyses undertaken during design, assumptions regarding the level of congestion in the module (in the absence of detailed design information) are critical. Explosion overpressures have, in the past, been significantly underestimated during the early stages of design.

- The interaction of explosion overpressures with structural response is not well understood.

STRATEGY DEVELOPMENT ISSUES

Understanding of explosion phenomena

Experimental data

- Undertake a critical review of the large-scale experimental data from the JIP tests in order to maximise the information available from the tests.

Realistic releases

- Improve understanding of the results of the JIP Phase 3B realistic release tests and interaction of gas releases with ventilation.

- Assess how representative the so-called realistic gas clouds used in explosion tests are of the actual conditions that could occur in a real incident.

Mist explosions

- Encourage the development of diagnostic techniques for characterising transient mist clouds.

- Promote small-scale experimental work on mist explosions to gain a better understanding of the basic mechanisms and aid the assessment of the consequences of these explosions.

- In the longer term, consider the undertaking of larger scale experiments on mist explosions.

Explosion modelling

Short term

- Promote best practice in the application of CFD and other modelling techniques to gas explosion modelling.

- Encourage organisations to ensure that the person carrying out CFD calculations has a thorough understanding of fluid mechanics, combustion and CFD – possibly also putting a 'buddy' system into place, thereby ensuring that quality checks are carried out.

- Investigate possible differences in results between different versions of codes used in industry.

- The level of inconsistency between exceedance curve approaches is of concern and requires further discussion and appraisal.

- Encourage more openness from the code developers with regard to:

  - the results of the validation exercises – perhaps with a document outlining the validation cases, etc; and

  - the numerical and modelling techniques implemented in the CFD codes.

Longer term

- Encourage CFD code developers to:

  - incorporate better physical sub-models for ignition, laminar flame growth and turbulent combustion,

  - incorporate better turbulence models, an accurate model for the transition from laminar to turbulent flow, and improved two-phase flow models

  - incorporate more accurate differencing schemes and more efficient solvers, which are robust,

  - introduce mesh refinement and de-refinement so that flame fronts and obstacles can be resolved properly.

- Encourage more validation, i.e. not calibration or ‘tuning’, of the CFD codes and their constituent sub-models.

- Improve understanding and modelling of the interaction of explosions with structural response.

FIRE EFFECTS

BACKGROUND

Direct effects of fire on personnel are generally regarded as fatal. The predominant, non-direct effect of thermal radiation can vary greatly depending on factors such as the heat output of the source, the distance of the personnel from the source, the duration of exposure and the atmospheric conditions. The effect of fire on personnel is an important factor in the design and operation of process plant, as it impacts greatly on the outcome of safety case assessments.

If a pressurised vessel is attacked by fire, its temperature rises and this reduces the strength of the vessel. This, combined with the pressure within the vessel, may lead to vessel failure within a short time (minutes) with catastrophic consequences.

STRATEGY OBJECTIVES

- To identify where the effects of fire are significant on personnel and process plant;
- To identify areas of uncertainty in analysing the effects of fire on personnel and equipment;
- Initiate research to increase knowledge and understanding in ill-defined areas of fire effects; and
- Promote the use of a consistent methodology for evaluation of fire effects on personnel and plant.

CURRENT KNOWLEDGE OF FIRE EFFECTS

Effect on people

In general, the direct contact of personnel with fire is relatively simple to determine. It is much more difficult to assess the non-direct effect of fires on personnel

Smoke and toxic gases

Carbon dioxide is toxic above 5% concentration and causes hyperventilation above 2% where the subject may inhale large quantities of other toxic components contained in smoke. Hydrogen cyanide will incapacitate a subject within minutes and sulphur dioxide and nitrous oxide have similar effects. Virtually all hydrocarbons will generate smoke. Dense smoke production will obscure escape routes. Smoke inhalation may cause death some hours after exposure.

Hot gases and hot objects

Objects with temperatures above 45°C may cause pain if in contact with skin for more than 10 s and those with temperatures above 100°C will cause burns within seconds. Convected hot air or hot gases above 120°C will result in skin pain after 10 minutes. Below this temperature cooling by sweating is possible, giving longer endurance times.

Thermal radiation

Physiological effects of thermal radiation may involve voluntary exposure over relatively long times (e.g. many minutes). The effects typically include high pulse rates, increased and laboured respiration, increased sweating and increased body temperature. The effects may be increased with increasing temperature, up to the point where pain/injury occurs.

At skin temperatures above 44°C, pain is felt and injury continues whilst the temperature remains above this point. The rate of injury increases by a factor of 3 for every degree above 44°C, such that at 50°C, the injury rate is ~100 times that at 44°C. In addition, for heat fluxes greater than 12.5 kW m^{-2}, 33% of the final burn occurs during cooling.

The extent of injury is often related to the thermal dose, which may involve a high heat flux over a short duration. Thermal radiation is a particular hazard in the event of fire balls or where escape routes are blocked by fire.

Process plant

Heat loads from fire attack, implicit in the current guidance (i.e. API 521), are much lower than can be expected in severe fires (up to 350 kW m^{-2}), that may occur on offshore installations and thus the process blowdown system may not guarantee vessel protection.

AREAS OF UNCERTAINTY

In general, there is insufficient information available on the failure modes, times and conditions for offshore vessels. The main area of concern relates to the effects of fires on pressurised systems and improved guidance, which identifies the key parameters that should be used in design, is needed.

The effectiveness of safety measures such as water deluge, passive fire protection and blowdown need to be carefully evaluated particularly if they feature in an ALARP demonstration.

INDUSTRY PRACTICE IN ASSESSMENT OF FIRE EFFECTS

Heat effects on personnel are evaluated using simple and pessimistic Rule Sets based on human response to 5, 12.5 and 37.5 kW m^{-2}. Escape is assumed at 5 kW m^{-2} but fatalities within minutes assumed at 12.5 kW m^{-2} and instantaneous death at 37.5 kW m^{-2}.

Fire attack on process plant is currently calculated based on the API 521 guidance that underestimates the heat load from pool and jet fires.

Time to failure determines the time available for evacuation and for shutdown or inventory dumping before escalation occurs.

STRATEGY DEVELOPMENT ISSUES

- To develop an improved specification of the characteristics of the fires that need to be considered in design.
- To develop a more accurate understanding of the failure conditions of vessels under fire loading, and hence produce a more effective design standard to replace API 521.
- To develop an improved understanding of the smoke and fume paths around installations and produce guidance to disseminate the information.

EXPLOSION CONSEQUENCE ASSESSMENT

BACKGROUND

Blast injury to people may comprise either direct effects (e.g. ear drum rupture) or indirect effects (injury due to flying debris). Blast damage to equipment of structures can result from either loading (applicable to large objects, e.g. walls) or drag loading (applicable to objects of narrow cross-section, e.g. pipework or primary steelwork) or a combination of the two. The extent of damage is dependent not only on the peak overpressure, but also the blast wave duration, impulse and rise time.

Of the 10 significant (> 0.2 bar) explosions which have occurred on offshore installations in the North Sea over the 25 year period 1973-97, all have resulted in significant damage to the installation, whilst 5 have caused injuries or fatalities (Vinnem, 1998).

CURRENT POSITION

Our understanding of the effects of explosions on people is, to a large extent, based on the observed far-field effects of conventional or nuclear weapons, which is of limited relevance to gas explosions on offshore installations. Our understanding of the effects of gas explosions on equipment and structures has advanced through the various phases of the JIP (Phase 2, Phase 3a and Phase 3b) each of which included some structural response experiments. However recent interpretation of some of this data has shown the importance of considering the response characteristics of a structure, as well as the explosion overpressure, in determining the loading imposed on such structures.

MODELLING CAPABILITIES

Current models for assessment of blast injury to people are based on the far-field effects of condensed phase explosions (as noted above) and therefore their application to gas explosions on offshore installations is highly uncertain. The prediction of explosion loading on equipment and structures (and their response) is likewise highly uncertain. This has been shown through the various model evaluation exercises undertaken as part of the JIP. Other aspects of concern include the prediction of localised explosion loads, e.g. on objects of narrow cross-section such as primary steelwork, and the uncertain validation of blast wave codes. The modelling of escalation (e.g. through blast or missile effects) is also an area of significant uncertainty, with little detailed guidance available.

INDUSTRY PRACTICE

Safety Case assessments of blast injury to persons are largely judgmental, making use of what little data there is of relevance to the near-field effects of gas explosions. Assessments of the effect of blast on equipment and structures is sophisticated for new installations (e.g. using CFD for explosion prediction and non-linear finite element analysis for structural response) but highly variable for existing installations, ranging from purely qualitative analysis to the use of advanced computational models or experimental techniques. Escalation modelling is performed to widely-varying degrees of rigour.

STRATEGY DEVELOPMENT ISSUES

Effects of blast on people

- Analysis of the effect of blast on people are highly uncertain as they are based on injury models developed from condensed phase explosions. They generally therefore to take a conservative approach, considering that all or a proportion of personnel in the vicinity of an explosion will be fatalities. A probit approach is not used due to the small distances involved.

- On offshore installations injury to personnel will be determined to a significant degree by secondary effects (e.g. collapsing structures, falling debris etc) and are not taken into account in risk assessments.

Effects of blast on equipment and structures

- The ability to predict, within reasonable accuracy, the explosion loads imposed on equipment and structures by hydrocarbon gas explosions is an essential element in the control of explosion risks on offshore installations.

- Currently there is uncertainty as to how to interpret overpressure data from large scale experiments for the purpose of understanding the loads imposed on equipment and structures, although it is anticipated that the Phase 3b work may shed further light on this.

- Current modelling capability falls short in a number of respects:

  - the prediction of loads on objects which are small or of narrow cross-section (e.g. pipework, primary steel work etc) or the localised loads on larger objects; and

  - uncertainty as to the validation of models used to predict ‘far-field’ explosion loads.

- Industry approaches to the assessment of explosion loads and structural response are of widely-varying rigour, particularly for existing installations.

- An initial study using coupled explosion prediction and structural response codes has shown that current (uncoupled) approaches may be giving significant overestimates of explosion loading.

Escalation modelling

- Escalation modelling is an important aspect of the hazard assessment and risk management of an installation especially in relation to TR impairment, giving key information on potential remedial measures to break a sequence of hazardous events.

- Treatments of escalation in QRA studies vary widely in their degree of rigour.

- Some potential mechanisms of escalation (e.g. missiles, partial blast wall failure, far field explosion effects on TR structures) appear not be given any specific consideration.

- Guidance on escalation modelling (UKOOA, 1995 and CMPT, 1999) is high level and broad in nature.

PREVENTION AND CONTROL OF FIRES

BACKGROUND

Preventative measures are the most effective means of minimising the probability of equipment failure and its associated risk. Protection systems are not substitutes for well-designed and well-maintained detection, warning and shutdown systems. However, they can protect the structure and process equipment, limit damage to these facilities and prevent escalation of fire.

Design features can be provided, such as shielding which can reduce the likelihood of vessel failure. The choice between active and passive systems (or their combination) is influenced by the protection philosophy, the fire type and duration, the equipment or structure requiring protection, water availability and the time required for evacuation. In all cases, the specification must be matched to the fire type and exposure. The various types of protection system are considered in more detail below.

STRATEGY OBJECTIVES

- Identify the most cost effective prevention and control measures that have the most significant benefit to personnel and process plant;
- To identify areas of uncertainty in analysing the effects of fire;
- Initiate research to increase knowledge and understanding in ill-defined areas of fire effects, and the corresponding prevention and control measures; and
- Promote the use of a consistent methodology for evaluation of cost effective prevention and control measures.

CURRENT KNOWLEDGE OF PREVENTION AND CONTROL MEASURES

There are two categories of prevention and control of fires; passive protection and active control and protection.

Passive fire protection (PFP) is defined, in the recently issued ISO standard (ISO, 1999), as “a coating, cladding or free-standing system which, in the event of a fire, will provide thermal protection to restrict the rate at which heat is transmitted to the object or area being protected”. These materials are used to:

(i) Prevent escalation of the fire due to progressive releases of inventory, by separating the different fire risk areas, and hence protect personnel until safe evacuation can take place,

(ii) Protect essential safety items and critical components such as separators, risers and topside emergency shutdown valves,

(iii) Minimise damage by protecting the critical structural members, particularly those which support the temporary refuge, escape routes and critical equipment.

Spray applied epoxy intumescent and subliming coatings are most frequently used now, although cementitious materials were extensively used in the past.

Active “protection” consists of several systems that may require human intervention to initiate. These include ESD and blowdown mechanisms, water deluge and foam systems, monitors, inerting systems, fire extinguishers etc. The installation and activation of these systems is well understood, although the physics of water droplet size and mists, on explosions hazards may require further work. The primary form of active fire protection for hydrocarbon processing areas is fixed deluge. Such systems may be provided to:

- Control pool fires and thus reduce the likelihood of escalation;
- Provide cooling of equipment (except that impinged by jet fires);
- Provide a means to apply foam to extinguish hydrocarbon pool fires; and
- Limit effects of fires (e.g. radiation, smoke movement) to facilitate emergency response and evacuation, escape and rescue (EER) activities.

AREAS OF UNCERTAINTY

There is an HSE cross-divisional need (preliminary steps are being taken) to develop guidance on the use and operational requirements for passive fire protection materials. At present, there is a lack of consistency in the requirements for protection of pressure vessels. This is reinforced by the recommendation in the HSE report on the Associated Octel incident that "HSE, in conjunction with the industry, should consider what guidance, if any, should be published on the provision of passive fire protection on vessels." This should include;

- A ‘standard’ fire test. This is required because furnace-based fire tests do not relate to conditions in “real” fires. There was a requirement for fire tests with a manageable, reproducible, well-characterised flame which is used in conditions which can be related to those in a “real” fire;
- Investigation of the effects of water streams on the performance of PFP,

- The effect of the size and nature of damage or penetrations, and the effect they have on the performance of PFP,
- The effect of blast overpressure on PFP,
- The effectiveness of protective systems for flange connections (possibly a variant of the Jet Fire Resistance Test),
- Consideration of secondary smoke and toxic gas emissions in the context of those from the primary fire.

INDUSTRY PRACTICE IN PREVENTION AND CONTROL OF FIRE HAZARDS

PFP is generally applied using ISO 13702, where the following functional requirements are given:

- PFP shall be provided in accordance with the Fire and Explosion Strategy,
- PFP of essential systems and equipment, or enclosures containing such systems and equipment, shall be provided where failure in a fire is intolerable;
- Where PFP is required to provide protection following an explosion, it shall be designed and installed such that deformation of the substrate caused by an explosion will not affect its performance;
- Selection of the PFP systems shall take into account the duration of protection required, the type and size of fire which may be experienced, the limiting temperature for the structure/equipment to be protected, the environment, application and maintenance, and smoke generation in fire situations.

Active prevention systems are also based on the FES, but with significant input from QRA studies. Active systems are considerably more expensive to install and maintain and hence further justification is required.

QRA studies usually take some degree of credit for operation of active fire protection systems. These systems are usually designated as Safety Critical Elements (SCEs), pursuant to the requirements of the DCR Regulations and have associated performance standards, in accordance with the requirements of PFEER.

STRATEGY DEVELOPMENT ISSUES

Passive fire protection

- To develop effective guidance on the use and operational requirements for passive fire protection materials including,
- The assessment of the size and nature of damage or penetrations that would lead to a significant reduction in performance,
- Establishment of a standard system of assessing the effect of blast overpressure on PFP,
- Determination of the effects of water streams on the performance of PFP.

Active fire protection

- To develop accurate guidance on the design of emergency depressurisation systems that consider the recently identified higher fire loading;
- To ensure that a specific hazard identification profile for each vessels and pipework is carried out;
- To produce improved information on the response of pressurised systems to fire to allow proper assessment of failure times and development of improved models/designs for fire loading.
- Review of the detailed findings of the EU FOAMSPEX project and assessment of their significance for the adequacy of foam systems used on offshore installations.
- To investigate improved design of directed deluge systems;
- To updated guidance on the use / replacement of halon systems.

PREVENTION, CONTROL AND MITIGATION OF EXPLOSIONS

BACKGROUND

A wide variety of measures may be employed to prevent, control and mitigate the effects of explosions. Whilst the emphasis should always be on explosion prevention (e.g. through prevention of leaks or elimination of ignition sources), the possibility of accumulation and subsequent ignition of a flammable hydrocarbon-air mixture cannot always be eliminated. Therefore control and mitigation measures may additionally be required.

CURRENT POSITION

Current standards for the selection and specification of measures to prevent, control and mitigate the effects of explosions comprise:

UK

- UKOOA Fire and Explosion Hazard Management Guidelines (UKOOA, 1995)
- Interim Guidance Notes (SCI, 1992) and associated Technical Notes.
- UKOOA/HSE Fire and Explosion Guidance Part 0: Fire and Explosion Hazard Management, Oct 2003.
- UKOOA/HSE Fire and Explosion Guidance Part 1: Avoidance and Mitigation of Explosions, Oct 2003.

International

- ISO/FDIS 13702, Petroleum and Natural Gas Industries - Control and Mitigation of Fires and Explosions on Offshore Production Installations - Requirements and Guidelines (ISO, 1998).
- NORSOK Standard S-001, Rev 3, Technical Safety (NORSOK, 2000).
- API RP2A (21^{st} Ed) Section 18.
- Engineering Handbook on the Design of Offshore Facilities to Resist Gas Explosion Hazard (Czujko, 2001).

Corporate

- BP Corporation ‘Guidance for the Protection of Offshore Structures against Fires and Explosions’ (BP, 2001) (See also Walker et al, 2001).

The Interim Guidance Notes have been updated (above), whilst the API RP2A standard has been replaced with a new standard ‘Design and Assessment of Offshore Structures for Fire and Blast’. The recent BP guidance (see above) forms the basis for the new API standard.

INDUSTRY PRACTICE

Since the Piper Alpha disaster installations in the UK sector of the North Sea have undergone significant modification to prevent, control and mitigate the effects of explosions. From Safety Cases reviewed recently, significant modifications continue to be implemented as the understanding of explosion hazards improves. For new installations a wide variety of measures are being employed with the emphasis on measures to prevent explosions or reduce explosion overpressures through good ventilation and installation layout.

KEY ISSUES

- **Limit State Approach to Blast Resistant Design**. This approach is widely used in the field of structural design. It forms the basis of the new BP guidance (BP, 2001) on fire and explosion engineering and has been utilised in the update of the Interim Guidance Notes. Its main advantage is that it avoids the use of an arbitrary design explosion load, but instead introduces a probabilistic element. Various limit states are defined with associated levels of performance (e.g. 10^{-3} per year event - elastic response; 10^{-5} per year event - plastic deformation, but not collapse). It can also take explicit account of the uncertainty associated with the loading event, although this aspect is not yet developed for gas explosions. Of concern to OSD is how the limit state approach fits in with the ultimate criteria that explosion risks should be ALARP. The limit state approach may place undue emphasis on the prediction of the probability of a given severity of explosion (highly uncertain), whereas under the ALARP principle OSD may look for low cost strengthening measures regardless of the predicted explosion frequency.

- **Scope of current guidance on explosion prevention, control and mitigation systems.** In the development the new BP guidance for fire and explosion engineering, Walker et al (2001) identified various shortfalls in the Interim Guidance Notes. These included:

  - explosion drag load estimation (important for blast resistant design of pipework, supports, primary structure etc);

  - simple methods for the calculation of blast wave loading on adjacent structures;

  - structural details for blast resistance; and

  - floating structure issues.

- Technical Note 2 (Explosion Mitigation Systems), published in 1994, has been superseded by the UKOOA/HSE Fire and Explosion Guidance for Fire and Explosion Hazard Management and Avoidance and Mitigation of Explosions.

- **Activation of water deluge on gas detection.** The advantages and disadvantages of activation of water deluge on gas detection has been the subject of considerable debate and study, e.g. see IGN Technical Note 2 (SCI, 1994), OTH 94 463, OTO 95 026, FABIG Technical Meeting 8 (SCI, 1996), OTO 2000 042 and FABIG Technical Meeting 20 (SCI, 2000). The effectiveness of deluge for explosion mitigation is dependant on module venting configuration and is not appropriate in all situations. This mitigation system has been adopted on some existing and newer installations (e.g. **Shearwater and Elgin/Franklin**). The main reason for non implementation in many cases appears to be the potential for water to enter electrical equipment and create an ignition hazard (as is believed to have occurred in two explosion incidents), requirements for uniform coverage and modifications to spray nozzles. A recent study commissioned by HSE (OTO 2000 042) concluded that 'activation of deluge on gas detection can make a significant improvement in the level of safety '… **providing the implementation is appropriate'**. The consensus appears to be activation of deluge on gas detection is not the universal answer. However, there is a lack of guidance as to the circumstances under which adoption of this mitigation measure would be beneficial and, if so, the design considerations which apply (deluge activation time, protection of electrical equipment, nozzle type, application rate etc). Issues relating to the benefits (or otherwise) of deluge on gas detection include:

  - the dependence of any risk reduction on the effectiveness of gas detection;
  - reliability initiation of deluge systems;
  - creation of turbulence, hence increased rate of pressure rise (initially);
  - low benefit in confined situations (low flame speeds);
  - issue of where gas is displaced to as a result of activation of deluge (e.g. to more hazardous location);
  - increased probability of ignition;
  - capability of deluge to provide explosion mitigation in addition to primary function, i.e. fire protection; and
  - enhanced corrosion of equipment.

- **Emerging technologies in the prevention, control and mitigation of explosions.** These technologies comprise: barrier technologies (Tam, 2000), water mist explosion suppression systems (Tam et al, 2000). The barrier technologies can be sub-divided as follows:

Inventory control barriers:

- Passive barriers: hard (e.g. blast walls)
  soft (membrane gas barriers)

- Active barriers: suppressive
  non-suppressive

Explosion development barriers (e.g. to control pressure piling effects or turbulence generation).

Some of these types of barrier have been implemented, e.g. 'weak wall' gas barriers and membrane gas barriers, whilst others are only at the concept stage. Some of the outstanding technical issues include the choice of materials for the barrier, the impact of the barrier during and after collapse, the impact on natural ventilation and consideration of equipment layout conducive to the implementation of barrier methods.

Water mist suppression systems utilising superheated water have been tested at medium scale under partial funding from HSE. This has demonstrated that such devices can suppress a developed explosion in a partially-confined module. However the proponents of this method recommend that a greater understanding of the interaction of mists and flames is obtained and that further testing is undertaken with different geometries and scales. The question of effectiveness of initiation the system on gas cloud ignition is also outstanding.

The efficacy of blast-induced atomisation from water containers has been demonstrated at small scale. Further work is required to develop and then test a device at large scale. A key advantage of this system is that it is passive (no activation required). The outstanding concerns are that are that it does not mitigate the effects explosions within a module (i.e. acts at the end of a duct or module boundary) and that it represents an additional mitigation system with an associated maintenance requirement.

- **Industry adherence to current guidance for the selection of prevention, control and mitigation measures**. It is not always apparent that the duty-holder had undertaken an assessment such as referred to in the UKOOA Guidelines (Fire and Explosion Hazard Management process), Interim Guidance Notes (flowchart for explosion resistance methodology) or ISO 13702 (Fire and Explosion Strategy). Through adherence to such guidance the duty holder's consideration of the hierarchy of available measures for explosion prevention, control and mitigation will be clearer.

- **Prevention, control and mitigation of explosions on floating installations.** A recent FABIG Technical Meeting (SCI, 2001) has highlighted a number of issues for floating installations which represent a challenge to existing design practices. These include:

  - diffraction and drag loading (both may be important on open decks),

  - explosion loading on the deck potentially leading to a cargo fire or loss of vessel integrity (FPSOs)

  - potentially severe turret explosion hazard with potential escalation to risers, deck, cargo tanks and/or TR impairment (FPSOs)

  - engine room explosions due to use of dual fuel engines (HP gas)

STRATEGY DEVELOPMENT ISSUES

Scope of current guidance on explosion prevention, control and mitigation

- The relationship between explosion risk assessment, the 'limit state' approach to blast resistant and the ALARP principle.

Activation of water deluge on detection of gas

- Consider the need for further guidance to better define the circumstances in which the activation of deluge on detection of gas is likely to be beneficial.

- Consider the need for further studies to support effective implementation of this measure (e.g. concerning deluge activation time, protection of electrical equipment, nozzle type, application rate etc).

Emerging technologies

- Maintain an up-to-date knowledge and appraisal of emerging technologies for the control and mitigation of explosions, some of which have both positive and negative impacts (e.g. gas barriers - prevent movement of gas, but may also hinder ventilation) whilst others are at the early stage of development (e.g. water mist suppression, use of passive water containers) with outstanding issues on cost and practicality.

Industry adherence to existing guidance on the explosion prevention, control and mitigation

  - Promote greater adherence by industry to existing guidance on the selection of explosion prevention, control and mitigation measures.

REFERENCES

Aberdeen D and Mansfield D (2001), “UKOOA draft scope of work for an ignition probability review and model development study”, 4 September 2001.

AIChE (1999), RELEASE: A Model with Data to Predict Aerosol Rainout in Accidental Releases, D W Johnson and J L Woodward, American Institute of Chemical Engineers – Centre for Chemical Process Safety.

Allen, J T (1998), Laser-based measurements of two-phase flashing propane jets: velocity profiles and droplet size distributions, J. Loss Prev Proc Ind, 11, pp291-297 and 299 – 306.

Allen, J T (2000), Qualitative Study of Impinging Flashing Jets on Realistic Surfaces, IR/L/FS/00/16.

API RP 521 (1997), Guide for pressure-relieving and depressuring systems, American Petroleum Institute, Fourth Edition.

Area Classification Code for Petroleum Installations. Draft second edition of Part 15 of Institute of Petroleum Model Code of Safe Practice in the Petroleum Industry, IP15.

Atkinson, G T (2001), Burning Rates in Hydrocarbon Compartment Fires, HSL Report, FS/01/17 (Draft).

Barton, J A and Moodie, K (1992), Project AA: Two-Phase Releases of Toxic and Flammable Substances - Thermal Initiation, Source Term and Fire Effects. Final Report: Overview of Project, HSE and CEC.

Bennet JF, Cotgreave T, Cowley L T and Shirvill L C (1990), Shell Offshore Flame Impingement Protection Programme (SOFIPP): Parts 1, 2 and 3, Shell Research Limited.

BP Corporation (2001), Guidance for the Protection of Offshore Structures against Fires and Explosions, API Draft 0, Sep 2001, MSL Services Corporation and BP Corporation.

BP Exploration (1997), SPR Operational Integrity Guidance on fire and gas detection.

BSI (1991). Ventilation principles and designing for natural ventilation. British Standards Institution, BS 5925:1991, Second Edition.

Butler C J and Royle M (2001), Experimental data acquisition of a new vapour cloud fire (VCF) modelling approach, HSL Internal Report PS/01/01.

Catlin C A (2001a), Passive Explosion Suppression by Blast-Induced Atomisation – The Intermediate Step between Small and Large Scale Demonstration (Confidential).

Catlin C A (2001b), Passive Explosion Suppression by Blast-Induced Atomisation from water Containers, ERA2001.

CCPS (1994), Guidelines for Evaluating the Characteristics of Vapour Cloud Explosions, Flash Fires and BLEVEs, CCPS/AIChemE, ISBN 0-8169-0474-X.

Chamberlain G A (1994), "An Experimental Study of Large-scale Compartment Fires", Trans.I.Chem.E. 72, Part B, pp. 211-219.

Chamberlain, G. A (1995), "An experimental study of water deluge on compartment fires", International conference and workshop on modelling and mitigating consequences of accidental releases of hazardous materials", American Institute of Chemical Engineers.

Chynoweth, S (2001), Dispersion in Congested Environments, ERA2001

Cleaver et al. (1998), Analysis of Gas Build-Up from High Pressure Natural Gas Releases in Naturally-Ventilated Offshore Modules, 7th Annual Conference on Offshore Installations: Fire ad Explosion Engineering, Church House Conference Centre, London, 2nd December, ERA 1998.

Cleaver et al. (1999), Analysis of Gas Build-Up from High Pressure Natural Gas Releases in Naturally-Ventilated Offshore Modules, 8th Annual Conference on Offshore Installations: Fire ad Explosion Engineering, Church House Conference Centre, London, 30th November, ERA 1999.

Cleaver R.P. and Britter R.E. (2001) FABIG Newsletter article R416, Issue 30, Oct. 2001, 'A workbook approach to estimating the flammable volume produced by a gas release'.

Cleaver, R P, Cronin P S, Evans J A and Hirst I L (2001), An experimental study of spreading liquid pools, Proc HAZARDS XVI Conf, 167.

CMPT (1999), A Guide to Quantitative Risk Assessment for Offshore Installations, 99/100, Centre for Marine and Petroleum Technology, J Spouge (Ed).

Cooper, M G (2001), A model for jet dispersion in a congested environment, HSE Contract Research Report 396/2001.

Cox A W, Lees F P and Ang M L (1990) Classification of hazardous locations, I.Chem.E.

Cracknell R F and Carsley A J (1997) Cloud fires: A methodology for hazard consequence modelling, Hazards XIII, process safety – the future, IChemE symp. Ser 141 (1997) 139

Czujko J (Ed) (2001), Engineering Handbook on the Design of Offshore Facilities to Resist Gas Explosion Hazard, CorrOcean.

Electrical apparatus for explosive gas atmospheres. Part 10. Classification of hazardous areas. Issue 2, (1996), BS EN 60079-10, (IEC 79-10 1995), November 1996.

Galbraith K (1998), Review of Blast Injury Data and Models, HSE Contract Research Report 192/1998.

Gosse A (1999), Large Scale Experiments to Study Jet Fires of Crude Oil/Gas Mixtures and Crude Oil/Gas/Water Mixtures", JIP managed by BG Technology.

Holen J (2001), Comparison of Five Corresponding Explosion Risk Studies Performed by Five Different Consultants, ERA2001.

HSE (1992), Gas/vapour build-up on offshore structures, OTI 92 591.

HSE (1992), The prediction of single and two-phase release rates, OTI 92 587.

HSE (1994), Smoke migration and ingress on offshore structures, OTN 94 165.

HSE (1995), Dispersion of sub-sea releases, OTH 95 465.

HSE (1999), A guide to the Control of Major Accident Hazards Regulations 1999, Guidance Booklet L111, HSE Books ISBN 0 7176 1604 5.

HSE (1999), Offshore hydrocarbon release statistics. HSE Internet

HSE (2004), A Critical Review of Post Piper Alpha Developments in Explosion Science For The offshore Industry, 2000. Research Report RR 089. HSE Internet.

HSE (2000) Offshore Hydrocarbon Releases Statistics, 1999. HSE Internet

ISO 13702, Petroleum and Natural Gas Industries – Control and Mitigation of Fires and Explosions on Offshore Production Installations – Requirements and Guidelines, ISO/FDIS 13702: 1998 (E).

ISO 15138, (2000), Petroleum and natural gas industries – Offshore production installations – Heating, ventilation and air-conditioning, International Standard ISO 15138:2000(E).

Kelsey, A (2000), CFD modelling of flashing jets: simulation of flashing propane jets, CM/00/02.

Lees (1996), Loss Prevention in the Process Industries, Butterworth-Heinemann, 2nd Ed.

Lewis M J (1998), Extension of a simple model for analysis of high pressure gas release to include impingement on plane surfaces. IR/L/CM/98/01.

Mahgerefteh, H, Saha P, and Economou, I G, A fast numerical simulation for full bore rupture of long pipelines containing high pressure two-phase hydrocarbons, AIChE Journal, 1999, 45(6), 1191-1201.

NORSOK (2000), Technical Safety, Standard S-001, Rev 3, Jan 2000

NORSOK H-001, (2001), Heating Ventilation and Air Conditioning, Rev. 4, Nov.

OSD PBN 98/20, (1998), Estimation of natural ventilation rates in low wind speed conditions.

OSD PBN 99/11, (1999). Ventilation and Dispersion Offshore.

Pratt, D (2001), HSE Initiatives on Process Integrity Management – An Update, ERA2001.

Ramsdale, S A and Tickle, G A (2000), Review of RELEASE rainout model and the Center for Chemical Process Safety (CCPS) data, HSE Contract Research Report 277/2000.

Rew P J, Deaves D and Maddison T (1995), Current Status and Advances in Flash Fire Modelling", Proceedings of International conference on modelling and mitigating consequences of accidental releases of hazardous materials, CCPS, New Orleans.

Rew P J, Deaves D M, Hockey S M and Lines I G (1996), “Review of Flash Fire Modelling”, HSE Contract Research Report No. 94/1996, ISBN 0 7176 1041 1.

Rew, P J and Hulbert, W G (1996), Development of Pool Fire Thermal Radiation Model, HSE Contract Research Report 96/1996.

Richardson, S M and Saville, G (1995), Blowdown of onshore and offshore installations, IChemE Symposium Series 139, 579.

Saunders et al (2001), A Study of the Natural Ventilation of Offshore Modules Using CFD Modelling and On-Site Measurements, ERA 2001.

Savvides C et al, (2001a), Dispersion of Fuel in Offshore Modules: Comparison of Predictions Using FLACS and Full-Scale Experiments, ERA 2001

Savvides C et al, (2001b), Dispersion of Fuel in Offshore Modules: Comparison of Predictions Using FLUENT and Full-Scale Experiments, ERA 2001.

SCI (1992), Interim Guidance Notes for the Design and Protection of Topsides Structures against Explosion and Fire, SCI-P-112/078, Jan 1992.

SCI (1994), Technical Note 2 - Explosion Mitigation Systems.

SCI (1996), Technical Meeting 8 - Explosion Mitigation with Water Deluge.

SCI (2000), Technical Meeting 20, Mitigation.

SCI (2001), Technical Meeting on ‘Fire & Blast Issues on Deepwater Platforms’.

Selby C A and Burgan B A (1998), Blast and Fire Engineering for Topside Structures - Phase 2: Final Summary Report, SCI Publication no. 253, The Steel Construction Institute ISBN 1 85942 078 8

SFPE (1995), SFPE Handbook of Fire Protection Engineering, Society of Fire Protection Engineers, 2nd Ed.

Shell UK Exploration and Production (1995), Code of Practice. Fire and gas detection and alarm systems for offshore installation. Shell UK.

Tam V (2000), Barrier Method: An Alternative Approach to Gas Explosion Control, FABIG Newsletter, R372, Issue 26.

Tam V et al (2000), Testing of the Micromist Device: an Active Soft Barrier for Explosion Control, ERA2000.

Topalis, P (1999), Multi-component thermodynamics in consequence analysis – Phase 1, HSE Contract Research Report 207/1999.

UKOOA (1995), Guidelines for Fire and Explosion Hazard Management, Issue 1, May 1995.

UKOOA/HSE Fire and Explosion Guidance Part 0: Fire and Explosion Hazard Management, Oct 2003.

UKOOA/HSE Fire and Explosion Guidance Part 1: Avoidance and Mitigation of Explosions, Oct 2003.

Vinnem J E (1998), Blast Load Frequency Distribution – Assessment of Historical Frequencies in the North Sea, Final Report Rev 3, Nov 1998, Report No. 19816-04 (a report by Preventor for Norsk Hydro).

Walker S et al (2001), Simplified Approaches to Fire and Explosion Engineering, ERA2001.

Witlox H and Bowen P (2002), Flashing liquid jets and two phase dispersion: A review, HSE Contract Research Report 403/2002.

WS Atkins, (2000) HSE Flash Fire Model Specification, WS Atkins Report No. AM5222-R1, Issue No. 2.