- rescue equipment
- evacuation equipment
- stand-by vessel

Administration of the emergency preparedness system concerns mainly the emergency organisation, its competence and awareness, experience feed-back, contingency plans and control of the adequacy of the established system for emergency preparedness.

Emergency preparedness is thus achieved and followed up systematically.

CONCLUSION

As pointed out in the introduction, major accidents in offshore petroleum activities often show common causes, such as poor design, inadequate organisation and slack maintenance of safety.

The NPD has decided to develop a consistent and logical legal framework concerning safety in petroleum activities, based on experience with major accidents, supervisory activities and research development. Safety is addressed as a complex quality concept which involves technology, people, both offshore and onshore, and operations.

Rules and regulations issued by the authorities have their limitations. At their best, they only reflect the risk-limits that the society can accept. In most cases, accidents will show regulations oversights and losses due to those events will be of a wide order for operating companies too.

Risk assessment, if performed seriously and in a safety management context, should allow for a better consciousness about the risk levels one can reasonably and intelligently accept. Risk should therefore be assessed in a wider perspective, especially a longer time perspective, than what is usually the case.

Accepting risks is a necessity, but it does not mean that one must expect an accidental event to occur. Risks have to be kept low and they must remain risks. This is not achieved automatically, solely by using experienced personnel and good engineering practice. Systematic, hard and sustained safety work is the only key.

FLACS AS A TOOL FOR SAFE DESIGN AGAINST ACCIDENTAL GAS EXPLOSIONS

Jan Roar Bakke, Dag Bjerketvedt and Magne Bjørkhaug[*]

SUMMARY

Recent accidents offshore and onshore have increased the focus on gas explosion safety. This paper provides an introduction to gas explosions and to R&D work on this subject at CMI.

A major result of CMI's efforts is a numerical tool, known as the FLACS code, for prediction of gas explosions in complex geometries. The code solves the full gas dynamic partial differential equations including the effects of turbulence and chemical reactions. FLACS has been applied in the design of more than 20 offshore platforms and for accident analyses after the West Vanguard and the Piper Alpha accidents. It is being increasingly used also for onshore process areas.

By applying FLACS it may be possible to suggest changes in process area design that will significantly affect explosion behaviour and hence overall safety. Correctly designed explosion venting is often able to reduce explosion pressure appreciably. FLACS simulations, as indeed all safety assessment, should start at an early stage in the design programme so that safety is an integrated part of design, not something that is added on. Simplified explosion calculation methods, in the form of nomograms or simple formulae, should in most cases where complex geometries are concerned not be used, since these do not account for the complex interactions often occurring in a gas explosion.

The layout of offshore modules and platforms is discussed. It is pointed out that explosion pressure depends strongly on the geometry. Some simple guidelines on how to improve gas explosion safety are presented. The most important is that explosion vent areas should be as large as possible. In order to obtain large explosion vent areas gas explosions should be on the design agenda from the start. Areas for further gas explosion research are also referred to.

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[*] Chr. Michelsen Institute,Dept. of Science and Technology,

Fantoftvn. 38, N-5036 Fantoft - Bergen, Norway.

INTRODUCTION

Gas safety is a source for concern in areas such as exploration, production, transport, processing, storage and utilization, where large amounts of gas may be accidentally released. Recent, large accidents involving gas explosions and fires demonstrate the need to continuously address gas safety issues[1,2].

Parts of the accident chain that may have to be addressed, include: leaks, dispersion, ignition, explosions, fires and subsequent loads on people and structures. Possible measures to improve safety include looking at process control, design and safety analysis, working procedures and 'the human factor' and also at mitigation techniques. All of these factors are important and must form part of a total safety control strategy.

For the last ten years research on gas explosions has been going on at CMI. Important knowledge has been generated and formalized through the development of tools like FLACS (FLame ACceleration Simulator)[3,4]. CMI's R&D work within gas explosion safety is concerned with design and safety analysis and with mitigation techniques.

A BRIEF INTRODUCTION TO GAS EXPLOSIONS

The objective of this chapter is to illustrate the principle of how geometrical conditions such as confinement, obstacles and venting are influencing explosion pressure. The load from a gas explosion will also be discussed.

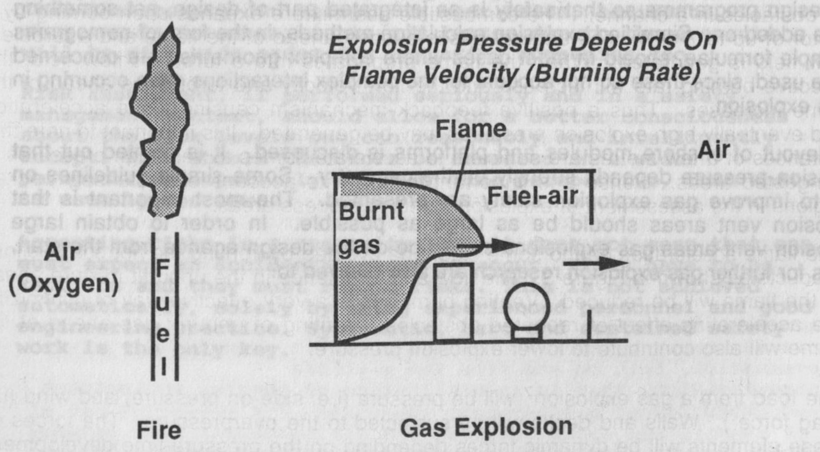

Figure 1: Illustration of jet-fire and gas explosion

Gas explosions are a result of <u>fast</u> liberation of chemically bound energy due to combustion of premixed fuel-air clouds. In an unconfined or partly confined area the flame speed (i.e. burning rate) is controlling the explosion pressure. Flame speeds in excess of 100 m/s are required in order to obtain damaging pressure waves[5].

In an accidental gas explosion the flame will normally start out as a slow laminar flame with a velocity of the order of 1 m/s. If the cloud is truly unconfined and unobstructed (i.e. no equipment or other structures engulfed by the cloud) the flame is not likely to accelerate to velocities of more than 20-25 m/s, and the overpressure will be negligible. The other extreme is the case of total confinement, where the pressure may end up at approximately 8 bar.

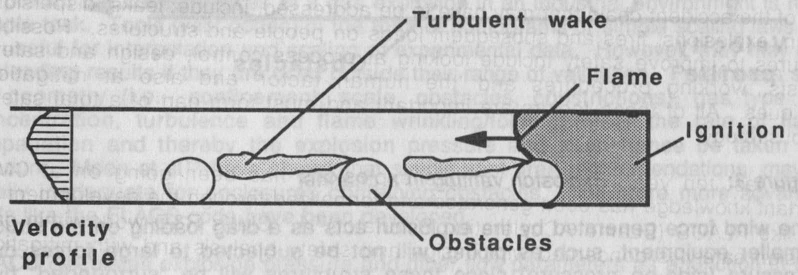

Figure 2: Flame acceleration in a channel due to turbulence caused by repeated obstacles

In a partly confined area with obstacles the flame may accelerate to several hundred meters per second[6]. The main mechanism of flame acceleration under such conditions is turbulent mixing. Figure 2 shows how this turbulence can be generated by obstacles in a channel. The combustible gas mixture expands upon burning by a factor of up to 7 or 8. The unburnt gas is pushed ahead of the flame and a turbulent flow field is generated. When the flame propagates into a turbulent flow field, the effective burning rate will increase and the flow velocity and turbulence ahead of the flame increases. Thus a positive feedback mechanism causing flame acceleration and eventually high explosion pressures may be generated. It is important to note that distances of a few metres are sufficient to accelerate flames to very high pressures in congested areas. Hence it is important to take into account local, densely packed regions in the assessment of explosion safety in process areas.

The flame acceleration can to some extent be avoided by venting the hot combustions products as shown in Figure 3. The flow and turbulence in the unburnt mixture ahead of the flame will be reduced. Venting burnt gas is a very effective way of minimizing the accelerating effect of repeated obstacles. Venting of unburnt gas ahead of the flame will also contribute to lower explosion pressure.

The load from a gas explosion[7] will be pressure (i.e. side-on pressure) and wind (i.e. drag force). Walls and decks will be subjected to the overpressure. The forces on these elements will be dynamic forces depending on the pressure-time development. The structural response will depend on the pressure-time curve and the natural frequency of the structure element. It is not only the maximum pressure that is important, but also the rise time and duration of the pressure-time curve. One way of characterizing the pressure-time curve is to use the time integral of the pressure, known as the impulse.

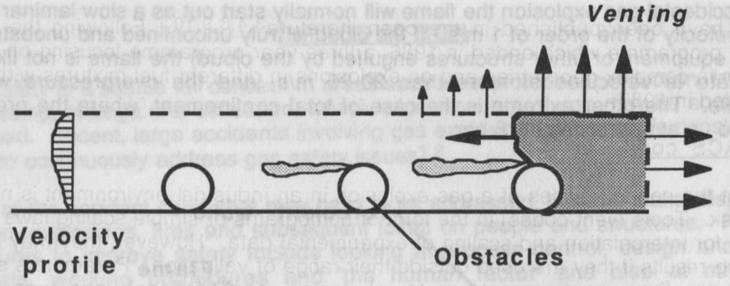

Figure 3: *Explosion venting in a channel*

The wind force generated by the explosion acts as a drag loading on the structure. Smaller equipment, such as piping, will not be subjected to large forces due to pressure (side-on pressure) since these structures will be "surrounded" by the pressure on a time scale of the order of one millisecond.

GAS EXPLOSION R&D AT CMI

Gas explosion research has been an important activity at Chr. Michelsen Institute (CMI) since the late 1970´s. The overall objective of the research has been to minimize gas explosion hazards both onshore and offshore. This has been achieved by generating new knowledge in answer to questions like

- what is the likely distribution in time and space of turbulence and fuel of hydrocarbon-air clouds generated by accidental releases?
- what kind of flame acceleration mechanisms, due to confinement and geometry, can be expected, and what will be the expected maximum explosion pressures in the system?
- what are the possibilities for successful venting of a confined explosion?

Answers to these questions were required to enable the generation of practical design principles to minimize the effect of accidental gas explosions.

In the experimental work pressure development due to flame acceleration by obstacle-generated turbulence was studied. This mechanism was identified as being mainly responsible for explosions occurring in complex geometries typically found on offshore platforms. The phenomenon was studied both in small and intermediate scale (0.2 m^3 and 50 m^3) for geometrical layouts of increasing complexity. The most complex layout was a scale 1:5 offshore module[8,9]. Different gases and ignition strengths were studied, as were ignition positions and vent arrangements.

Results from these experiments served two purposes: they provided new insight and also data for validation of computer codes developed for explosion overpressure prediction. These codes, which were named FLACS (Flame Acceleration Simulator), concentrated on modelling of compressible, turbulent reactive flows and on numerical solution of the resulting set of partial differential equations. Some results from the research have been published in the open literature[3,4,8,9,10]. Following the gas explosion programme which ended in 1986, a three-year programme focusing on gas dispersion in complex geometries and on explosions in different fuel mixtures with air was initiated in 1987.

The FLACS code

To predict the concequences of a gas explosion in an industrial environment is not a simple task. Tools (vent codes) in the form of nomograms or simple scaling laws can be useful for interpolation and scaling of experimental data. However, they may give misleading results if they are used outside their range of validation. Parameters such as geometry (i.e. confinement, scale, obstacles, constrictions), gas type and concentration, turbulence and flame wrinkling/folding affect the rate of flame propagation and thereby the explosion pressure and must hence be taken into account. Moen et al[11] have shown that simple vent area recommendations may be totally inadequate for enclosures containing obstacles. Therefore more advanced tools like the FLACS-code have been developed.

FLACS calculates explosion pressure and other flow parameters as a function of time and space for different geometries and explosion scenarios. It takes account of the interaction between flame, vent areas and obstacles such as equipment and pipe work. Recent development of FLACS includes the ability to simulate dispersion in complex geometries, both with diffuse and high-momentum leaks, with or without wind.

The FLACS codes solve the full gas dynamic partial differential equations including the effects of turbulence and chemical reactions. The equations are discretized using a finite-volume technique and a weighted upwind/central differencing scheme for the convection terms. Velocities are calculated on staggered grids. The effect of turbulence is included through the eddy-viscosity concept by solving equations for turbulent kinetic energy and its rate of decay. Combustion is modelled by an equation for mass fraction of fuel containing a fuel consumption term based on a quasi-laminar formulation and on turbulent, mixing-limited combustion. Ignition is modelled by assuming that 50 % of the fuel in the control volume in which ignition occurs, is consumed. Thus the temperature is raised and the explosion starts. In many industrial geometries flame acceleration may be generated in areas where the geometrical details are too small to be resolved on the numerical grid. The geometrical details in these areas are represented by porosities, whereas empirical formulae depending upon obstacle types and shapes describe momentum loss and turbulence generation.

The validation of the FLACS-code was performed by comparing computer predictions with experimental results in four different test rig geometries (including scaled-down offshore modules) at two different scales.

CASD is a set of front-end programmes for the FLACS codes. The function of CASD is to simplify the generation of input data for FLACS, such as the geometry, the fuel-air cloud and ignition point(s). CASD is also used for presentation of FLACS output to generate simple time-series plots like pressure-, impulse-, and drag-time plots as well as coloured shaded-image contour representations of velocities, flame location, pressure etc. Three-dimensional animations of the explosion development can also be generated.

In explosion simulations using FLACS the following factors may be investigated:

- location of ignition point
- type of fuel
- size and fuel concentration of the combustible cloud
- size, location and type of explosion vent areas
- location and size of structural elements and equipment

The running of FLACS is an extensive numerical task which requires a fairly large computer. The three-dimensional Navier-Stokes equations, suitably expanded to include the effects of chemical reactions and turbulence, are discretized by employing a finite-volume technique. Combustion is modelled by a quasi-laminar formulation and a turbulent, mixing-limited combustion model.

At CMI the FLACS-code has been used for evaluation of more than 20 North Sea Platforms and some onshore installations. The code has also been applied in the investigation of the West Vanguard and Piper Alpha accidents. Simulated overpressures seem to correspond reasonably well with the levels of destruction that can be observed. The companies sponsoring the development of FLACS are using the programme internally.

MODULE AND PLATFORM LAYOUT

In this chapter we will discuss the influence of the module and platform layout on the explosion pressure. The important parameters are:

- module shape
- size, location and type of explosion vent areas
- location of equipment

Module shape and explosion venting

The module shape and the location of vent areas are closely linked. The size and the location of the vent areas should therefore depend on the module shape. For a module with explosion venting on two end walls the ideal shape is a cubical box. In a cubical module,with explosion ventilation on two sides, a relatively low explosion pressure may be expected. If the module is elongated and ventilation is only located on the smallest faces most explosion scenarios will give high pressures.

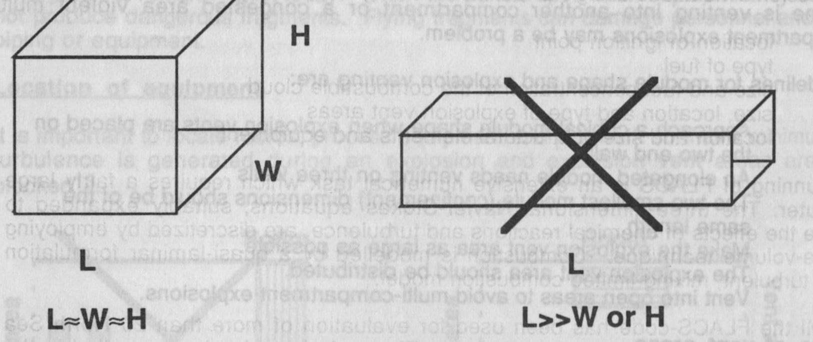

Figure 4: A cubical module provides better explosion venting for vent areas on two end walls

An elongated module is in principle a channel like in Figure 2. The flame can travel over a long distance and the conditions, i.e. limited venting, will support the flame acceleration. The flame will propagate in a planar propagation mode in the main part of the module. For the cubical module the flame will propagate in a spherical mode. A spherical mode of flame propagation requires higher flame velocity than a planar mode to generate the same explosion pressure. The pressure wave can expand more "freely" in the spherical mode.

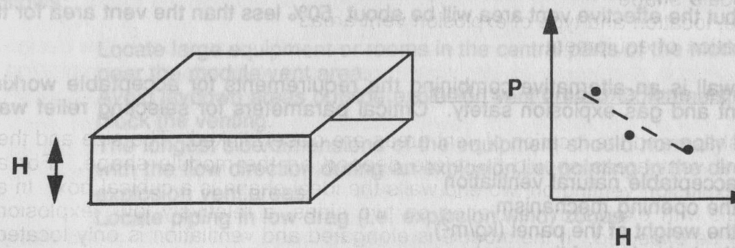

Figure 5: The height of the module can be important

We have experienced that the height of the module is often important, as illustrated in Figure 5. By increasing the height of the module the explosion pressure can in some cases be reduced. It may therefore be beneficial to replace solid decks with grated decks and thereby create a more cubical shape of confinement. Such an action should be viewed in relation to fire hazard and dispersion of gas.

In discussing Figure 3 it was pointed out that venting of hot combustion products is an effective way of minimizing flame acceleration and high explosion pressure. This effect can be utilized by venting through three walls of the module. In FLACS simulations and in experiments we observed a factor of up to 10 reduction in explosion pressure by opening one of the long side walls in a module. The deck or a side wall should hence be considered as possible venting areas.

The explosion venting should relieve into open areas with a minimum of obstructions. If one is venting into another compartment or a congested area violent multi-compartment explosions may be a problem.

Guidelines for module shape and explosion venting are:

- Approach a cubical module shape when explosion vents are placed on the two end walls.
- An elongated module needs venting on three walls
- The two smallest module (confinement) dimensions should be of the same length.
- Make the explosion vent area as large as possible.
- The explosion vent area should be distributed.
- Vent into open areas to avoid multi-compartment explosions.

Type of vent areas

The vent areas in the module normally consist of:

- open walls,
- louvered walls, or
- relief walls that open during an explosion.

The open wall is normally the best solution from an explosion point of view[12]. If a large part of the module is open, the natural ventilation will be good and the formation of explosive gas clouds will be less likely. If an explosion should occur, the open wall will relieve explosion pressure effectively. However, due to weather conditions in the North Sea, fully open walls are often impractical. A louvered wall will also act as a vent area, but the effective vent area will be about 50% less than the vent area for the open wall.

The relief wall is an alternative combining the requirements for acceptable working environment and gas explosion safety. Critical parameters for selecting relief walls should be:

- acceptable natural ventilation
- the opening mechanism
- the weight of the panel (kg/m^2)
- the behaviour of the panel

The use of relief walls (wind walls) should be limited so that acceptable natural ventilation is obtained under normal operation. Without natural ventilation even a small gas leak can build up a hazardous gas cloud. A relief wall should open as early as possible during an explosion, but not open due to wind. Our experience is that the design of the opening mechanism is rather difficult. Experimental testing with dynamic loads (i.e. explosion testing) appears to be required. Static testing of the opening mechanism does not produce relevant information. A panel that has a static opening pressure of 50 mbar, may not open before the pressure reaches 100-200 mbar if the load is from a gas explosion.

The weight of the panel (kg/m^2) will indicate how fast the panel will move after it has started to open. One should select relief walls with low panel weight. Wind walls with a weight of 5-10 kg/m^2 exist today. When the panels open in an explosion they should not produce dangerous fragments. Flying fragments can damage personnel and also piping or equipment.

Location of equipment

It is important to locate rooms, process equipment and pipework so that a minimum of turbulence is generated during an explosion and explosion vent areas are not blocked[13].

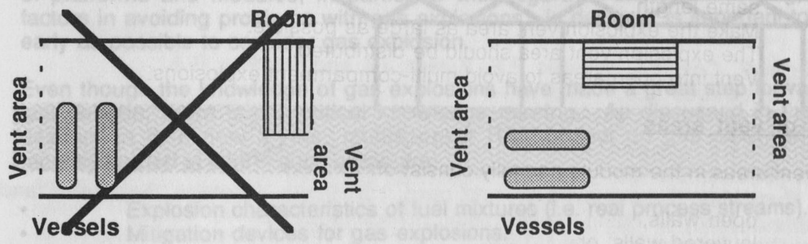

Figure 6: *Top view of two module layouts. On the left side the room and the vessels are blocking the vent area and generating turbulence. The right side shows an improved layout.*

Figure 6 shows how a room and two vessels are best located in a module with venting on the end walls. Some guidelines for locating the equipment can be given as follows:

- Locate large equipment or rooms in the central parts of the module, not near the module vent area.
- Avoid laydown areas outside explosion vent areas. Containers etc. will block the venting.
- The longest side/dimensions of the equipment should normally be parallel with the flow direction during an explosion,i.e. pointing in the direction of the explosion vent.areas.
- Locate piping in low drag (i.e. explosion wind) zones.

Platform Layout

The venting arrangement of the modules will influence the layout of the platform. If we go for cubically shaped modules with end ventilation it is possible to have modules located next to each other. The modules will then be separated by strong blast/fire walls.

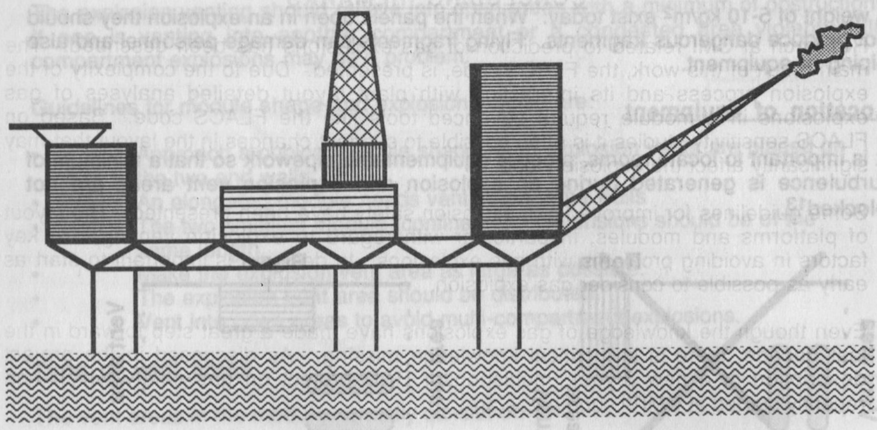

Figure 7: *Platform layout with open space between the various areas.*

The best explosion venting is obtained if the modules have explosion venting on three sides. Such modules will require open space between various areas . Figure 7 illustrates a platform layout with such open spaces. This layout provides exellent explosion venting. Potentially hazardous areas are in addition separated by blast/fire walls. An explosion in one area is not likely to propagate to neigbouring areas.

Gas explosion effects should be taken into account as early as possible in the design phase. It is difficult and costly to implement safety measures such as explosion venting at a late stage in the design. In the early phase of design one should focus on :

- Module shape and explosion venting
- Location and separation of various areas

If the simple guidelines given in this chapter are followed, one would avoid many problems in the later part of design. During detailed engineering more advanced tools for evaluation of gas explosions are required.

At CMI the FLACS-code has been used in simulations of gas explosions on more than 20 North Sea platforms. These platforms are both existing platforms and platforms under construction. The use of FLACS results for the design of the Shell Draugen Topsides is described by Cockbain et al[14].

CONCLUDING REMARKS

Research at CMI related to prediction of gas explosions has been described. The main result of this work, the FLACS code, is presented. Due to the complexity of the explosion process and its interaction with plant layout detailed analyses of gas explosions in a module require advanced tools like the FLACS code. Based on FLACS sensitivity studies it is often possible to suggest changes in the layout that may significantly affect the explosion load.

Some guidelines for improved gas explosion safety have been presented. The layout of platforms and modules, in particular with regard to explosion venting, are key factors in avoiding problems with gas explosions. In design it is important to start as early as possible to consider gas explosion.

Even though the knowledge of gas explosions have made a great step forward in the last decade, there is still critical knowledge missing. As discussed in the project description of a new 3-year, multisponsor R&D project on gas safety which has recently started at CMI[15] such areas are:

- Explosion characteristics of fuel mixtures (i.e. real process streams).
- Mitigation devices for gas explosions.
- Experimental investigation of structural loading of gas explosions.
- Flame propagation in pipe arrays and complex obstacles.
- Optimum explosion venting (Wall design for optimum explosion venting combined with acceptable natural ventilation rates for different module shapes).
- Larger scale experiments (Volume 2000 m^3 - 10000 m^3).

ACKNOWLEDGEMENTS

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THE APPLICATION OF RISK ASSESSMENT TO EXISTING INSTALLATIONS

R.A. Cox
Chief Executive, Four Elements Ltd
25 Victoria Street, London SW1H 0EX

SUMMARY

In the past, the application of risk assessment to offshore installations has been mainly in the context of new projects. The Norwegian Petroleum Directorate's "Guidelines for Safety Evaluation of Platform Conceptual Design" are an example of this. However, in the U.K. sector there are well over 100 major platforms which may require retrospective assessment using "Formal Safety Assessment" (FSA) or "Quantitative Risk Assessment" (QRA) techniques. This paper addresses the special issues which arise when such methods are applied to existing installations.

Among these issues, the following are discussed:

- o identification of remedial measures that are suitable for existing installations,
- o decision-making framework for selecting upgrade measures,
- o criteria for acceptability of risk for installations nearing the end of their productive life.

1.0 INTRODUCTION

There has been a pronounced trend in recent years towards the setting of safety **objectives** as the prime means of safety regulation, rather than the prescription of the **means** of achievement. This trend is in line with the philosophy of the U.K. Health and Safety at Work Act, 1974, which places a very general duty on operators to reduce risk to a level that is "as low as reasonably practicable".

Quantitative Risk Assessment (QRA) is a method of obtaining a measure of performance with respect to safety objectives, which has been developed primarily for the case of large scale accidents, which by their nature are very rare, and therefore their frequency cannot be obtained from statistics alone.