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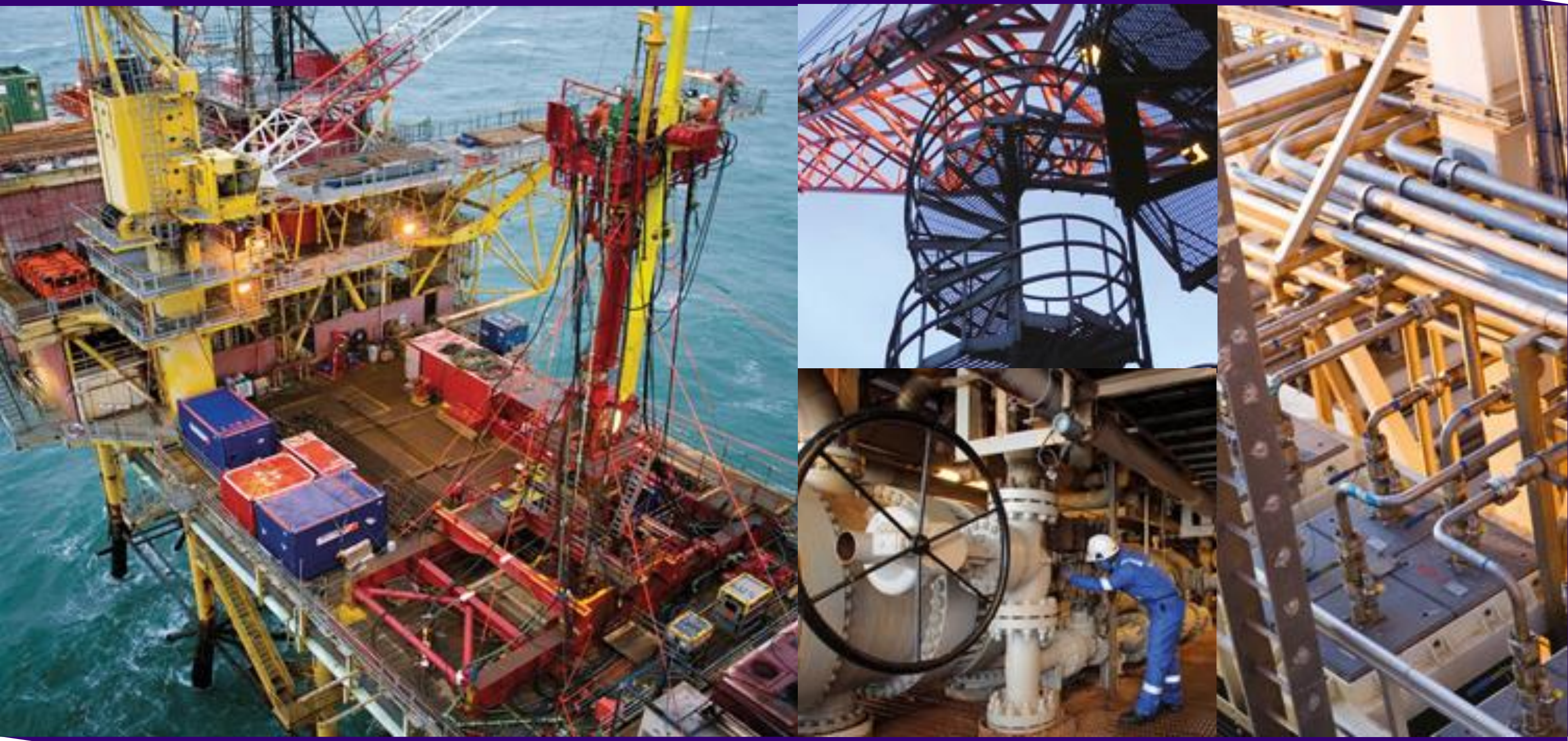

Fire and Explosion Guidance

Issue 2

March 2018

Acknowledgments

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ISBN: 1 903 004 73 2
PUBLISHED BY OIL & GAS UK

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In fond memory of Howard Thompson.

Howard was an eloquent and passionate advocate of safety engineering and inherently safer design who regularly spoke at industry events and mentored and inspired many young engineers.

Howard Thompson 1958-2016.

Fire and Explosion Guidance

March 2018

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List of Abbreviations

Abbreviations	Definitions
AFFF	Aqueous Film Forming Foam
AFP	Active Fire Protection
ALARP	As Low As Reasonably Practicable
API	American Petroleum Institute
APOSC	Assessment Principles for Offshore Safety Cases
AVM	Anti-vibration Mounts
BAT	Best Available Technique
BLEVE	Boiling Liquid Expanding Vapour Explosion
BST	Baker-Strehlow-Tang
CAM	Congestion Assessment Method
CBA	Cost-Benefit Analysis
CCTV	Closed-circuit Television
CFD	Computational Fluid Dynamics
CMAPP	Corporate Major Accident Prevention Policy
CMMS	Computerised Maintenance Management System
COMOPS	Combined Operations
DAF	Dynamic Amplification Factor
DAL	Dimensioning Accident Load
DCR	The Offshore Installations and Wells (Design and Construction, etc.) Regulations 1996
DDT	Deflagration to Detonation Transition
DIF	Dynamic Increase Factor
DLB	Ductility Level Blast
EER	Evacuation, Escape and Rescue
ENVID	Environmental Impacts Identification
ESD	Emergency Shutdown
ESDV	Emergency Shutdown Valve
ESSA	Emergency Systems Survivability Analysis
FEA	Finite Element Analysis
FEED	Front-end Engineering Design
FMEA	Failure Mode and Effects Analysis

Abbreviations	Definitions
FPSO	Floating, Production, Storage and Offloading Vessel
FSA	Functional Safety Assessment
FSO	Floating Storage and Offloading Vessel
GASCET	HSE Guidance for the Topic Assessment of the Major Accident Hazard Aspects of Safety Cases
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HEM	Homogeneous Equilibrium Model
HIPS	High Integrity Protection System
HIPPS	High Integrity Pressure Protection System
HIRA	Hazard Identification and Risk Assessment
HP/HT	High Pressure/High Temperature
HRA	Health Risk Assessment
HSE	UK Health and Safety Executive
HSL	UK Health and Safety Laboratory
HVAC	Heating, Ventilation and Air-conditioning
ICAF	Implied Cost of Averting a Fatality
ISD	Inherently Safer Design
JHA	Job Hazard Analysis
LFL	Lower Flammable Limit
LOPA	Layer of Protection Analysis
LOS	Line-of-Sight
LPG	Liquefied Petroleum Gas
MAH	Major Accident Hazard
MAR	The Offshore (Management and Administration) Regulations 1995
MDOF	Multi Degree of Freedom
MEI	Major Environmental Incident
MEM	Multi-Energy Method
MSF	Module Support Frame
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
NCCI	Non-Contradictory Complementary Information
NDP	Nationally Determined Parameters

Abbreviations	Definitions
NLFEA	Non-linear Finite Element Analysis
NOPSEMA	National Offshore Petroleum Safety and Environment Management Authority
NUI	Normally Unmanned Installation
OGUK	Oil & Gas UK
OIM	Offshore Installation Manager
OIS	HSE Offshore Information Sheet
ORA	Operational Risk Assessment
PDR	Porosity, Drag Resistance
PFEER	The Offshore Installations (Prevention of Fire & Explosions, and Emergency Response) Regulations 1995
PFP	Passive Fire Protection
PLL	Potential Loss of Life
POB	Personnel on Board
PSR	The Pipeline Safety Regulations 1996
PSV	Pressure Safety Valve
QRA	Quantitative Risk Assessment
SCR 2015	The Offshore Installations (Offshore Safety Directive) (Safety Case etc.) Regulations 2015
SDOF	Single Degree of Freedom
SECE	Safety and Environmentally Critical Element
SEP	Surface Emissive Power
SIF	Safety Instrumented Function
SIL	Safety Integrity Level
SIMOPS	Simultaneous Operations
SLB	Strength Level Blast
SEMS	Safety and Environmental Management System
SOLAS	The International Convention for the Safety of Life at Sea 1974
SRS	Safety Requirements Specification
TR	Temporary Refuge
TRIF	Temporary Refuge Impairment Frequency
UFL	Upper Flammable Limit
UKCS	United Kingdom Continental Shelf
UTS	Ultimate Tensile Stress

Abbreviations	Definitions
UV	Ultraviolet
VCE	Vapour Cloud Explosion
VID	Video Imaging Detection
VOC	Volatile Organic Compound

1 Introduction

This document sets out guidance and good practice for designing against fire and explosions on offshore installations. The guidance focuses on setting a philosophy for design and assessment in a realistic and accessible manner. In doing this, it provides a rational and pragmatic foundation to support design decisions, allowing the basis of such decisions to be understood and justified.

Topics addressed include fire and explosion hazard types, fire and explosion management, the derivation of fire loadings, heat transfer and explosion loads and the response of equipment and systems to fires and explosions.

This document was developed by the Fire and Explosion Working Group of the Oil & Gas UK (OGUK) Major Hazards Management Technical Group. This guidance supersedes the OGUK 'Fire and Explosion Guidance' – Issue 1 [1].

1.1 Purpose

The purpose of this document is to provide a technical reference for the understanding and management of fire and explosion risks throughout the lifecycle of offshore installations on the United Kingdom Continental Shelf (UKCS).

It is intended that this document be used during the design of, and when making operational modifications to, offshore installations in order to optimise and prioritise expenditure where it has most safety benefit.

This document covers topics associated with UK statutory provisions where they relate to the management of fire and explosion risks on offshore installations. These include:

- The Health and Safety at Work Act 1974.
- The Offshore Installations (Offshore Safety Directive) (Safety Case etc.) Regulations 2015 (SCR 2015).
- The Offshore Installations (Prevention of Fire & Explosions, and Emergency Response) Regulations 1995 (PFEER).
- The Pipeline Safety Regulations 1996 (PSR).
- The Offshore Installations and Wells (Design and Construction, etc.) Regulations 1996 (DCR).
- The Offshore (Management and Administration) Regulations 1995 (MAR).

The UK Health and Safety Executive (HSE) has published guidance on these regulations [2, 3, 4, 5, 6].

1.2 Objective

The objective of this document is to reduce risk to life, the environment and the integrity of offshore facilities exposed to fire and explosion hazards by providing guidance on practices and methods which can lead to their effective assessment and management.

The scope of this document is focused on offshore production and non-production installations operating on the UKCS.

Major environmental incidents

When introduced in July 2015, the scope of SCR 2015 was broadened to cover major environmental incidents (MEIs) which are defined as:

> *an incident which results, or is likely to result, in significant adverse effects on the environment in accordance with Directive 2004/35/EC of the European Parliament and of the Council on environmental liability with regard to the prevention and remedying of environmental damage*

It is implied in SCR 2015 that an MEI may result from a fire or explosion. Fire or explosion should not usually lead directly to a MEI; rather it is the secondary effects (e.g. escalation, major damage to structure of the installation, any resulting pollution e.g. from spills or combustion products) that can lead to damage to the environment (e.g. coastal margins). Therefore, whilst this document is of some relevance to MEIs, it has not been written specifically with this aim in mind. In this context, the document has been written with the understanding that management of MEI risk is evolving, and care should be taken to review the most recent guidance on this topic in combination with this document to ensure compliance and holistic management of risks to safety and the environment.

2 Fire and explosion hazard management philosophy

2.1 Aims of fire and explosion hazard management

Fire and explosion management aims to ensure that:

- All fire and explosion hazards have been identified, assessed, and are understood.
- The overall risks from fires and explosions are as low as reasonably practicable (ALARP), including the risk from the initiating event and subsequent escalation.
- An appropriate combination of prevention, detection, control and mitigation systems is implemented and maintained throughout the lifecycle of the installation.
- The systems provided to protect personnel from the effects of fires and explosions are suitable for these hazardous events and have performance standards commensurate with the required risk reduction.
- The design, operation and maintenance of the systems will be undertaken by competent staff who understand their responsibilities in the management of the hazards and possible hazardous events.
- Any changes to the installation, which may affect the likelihood or consequences of fires and explosions, are identified, assessed and the systems revised to take the changes into account as necessary.

In order to achieve these aims, effective and economic fire and explosion hazard management is needed, and this depends on the appropriate timing and use of resources. The following summarise the main principles:

- Fire and explosion assessment should commence very early in the design and should be used as one of the bases of hazard management throughout the installation lifecycle.
- All areas of the installation where there is potential for fire or explosion events to occur should be identified.
- Sufficient knowledge of the hazards and their contribution to the overall risks should be available to the engineering teams and be considered at design, commissioning, operation, maintenance and modification of the installation.
- The principles of inherently safer design should be applied early in the design so as to eliminate hazards, or where this is not achievable to reduce them, so far as is reasonably practicable, by:
  - The minimisation of the consequence of fire or explosion events.
  - The minimisation of the probability of occurrence of fire or explosion events.
  - The minimisation of the potential for escalation.
- Safety systems should be selected based on the hierarchy of prevention, detection, control and mitigation.
- A safety and environmental management system (SEMS) should be implemented which ensures that the above goals are consistently achieved

- An operational management system should be implemented to minimise the potential for fire or explosion events to occur throughout the lifetime of the installation including decommissioning and removal.
- Resources should be assigned to systems taking account of the risks from the hazardous events and the role of the system in reducing them.
- The hazard management process should be documented and communicated to operations personnel so that they have adequate information about the hazards, hazardous events and safety systems provided to manage them.

Escape and evacuation objectives

A further set of more specific goals ensure that personnel will reach a safe location in the event of a major accident event. These should be implemented as far as reasonably practicable, noting these goals are not achievable for all fire and explosion events (e.g. a large fire with smoke across the whole platform):

- That one escape route to the temporary refuge (TR) remains functional for the escape and recovery time of all personnel and emergency response teams, as appropriate.
- The TR and its supports will maintain their integrity in all design explosion events.
- That a means of evacuation is available for all personnel on board (POB).
- That all large inventories are isolated in the event of a design explosion event.
- The ability of personnel to escape from, and to shelter safely from the effects of a fire and/or explosion event and the ability to evacuate to a safe location where recovery can take place is not compromised.

Further advice on evacuation, escape and rescue (EER) in relation to PFEER can be found in HSE guidance [3].

2.2 The safety management system

Fire and explosion management, and process safety in general, should be encapsulated in a SEMS.

A SMS provides a framework to ensure, so far as is reasonably practicable, the health and safety of employees and other people affected by the work.

The system will demonstrate the means by which the organisation's safety policy is put into effect. The structure of the system should comply generally with accepted standards from the regulator and industry. Some of these are:

- International standards ISO 9001 [1] and ISO 14001 [2] in relation to quality and environmental management systems.
- HSE guidance HSG65 [3] on health and safety management using the HSE's 'Plan, Do, Check, Act' approach.
- British standard OHSAS 18001 [4] specific to occupational health and safety management systems.

- American Petroleum Institute (API) Recommended Practice API RP 75 [6] for safety and environmental management programs for offshore facilities.

All management systems will have the same basic elements:

- Policy and objectives.
- Organisation, resources and procedures.
- Risk identification and evaluation.
- Planning of work activities (including emergency response).
- Competency assurance and training.
- Communication of safety related information.
- Implementation and monitoring (including means of measuring performance).
- Audit to assess the operation of the SMS in practice.
- Review of system implementation and achievement of targets based on feedback from the monitoring system.

Corporate major accident prevention policy

In order to demonstrate the overall aims and arrangements for controlling the risk of major accident hazards (MAHs), including fires and explosions, and how these aims are to be achieved, a duty holder should develop a corporate major accident prevention policy (CMAPP). This is a commitment from the corporate level to demonstrate safety leadership, in keeping with the requirements of Regulation 7 of SCR 2015. The CMAPP should describe the following requirements and responsibilities:

- Maintaining a command and control system for the management of MAHs.
- Building and maintaining a strong safety and environmental culture.
- Maintain and build personnel competency to manage MAHs.
- Rewarding and recognising desirable behaviours.
- Reviewing CMAPP compliance and effectiveness, including capabilities and goals for management and control of MAHs and process auditing.
- Managing and controlling MAHs.
- Engaging workforce to review and comment on MAHs, risks and prevention and control measures.
- Providing and maintaining mechanisms to communicate, both to and from the workforce, issues concerning MAH management.

Further information about the CMAPP can be found in the HSE guide to SCR 2015 [5].

2.3 Risk based decision making

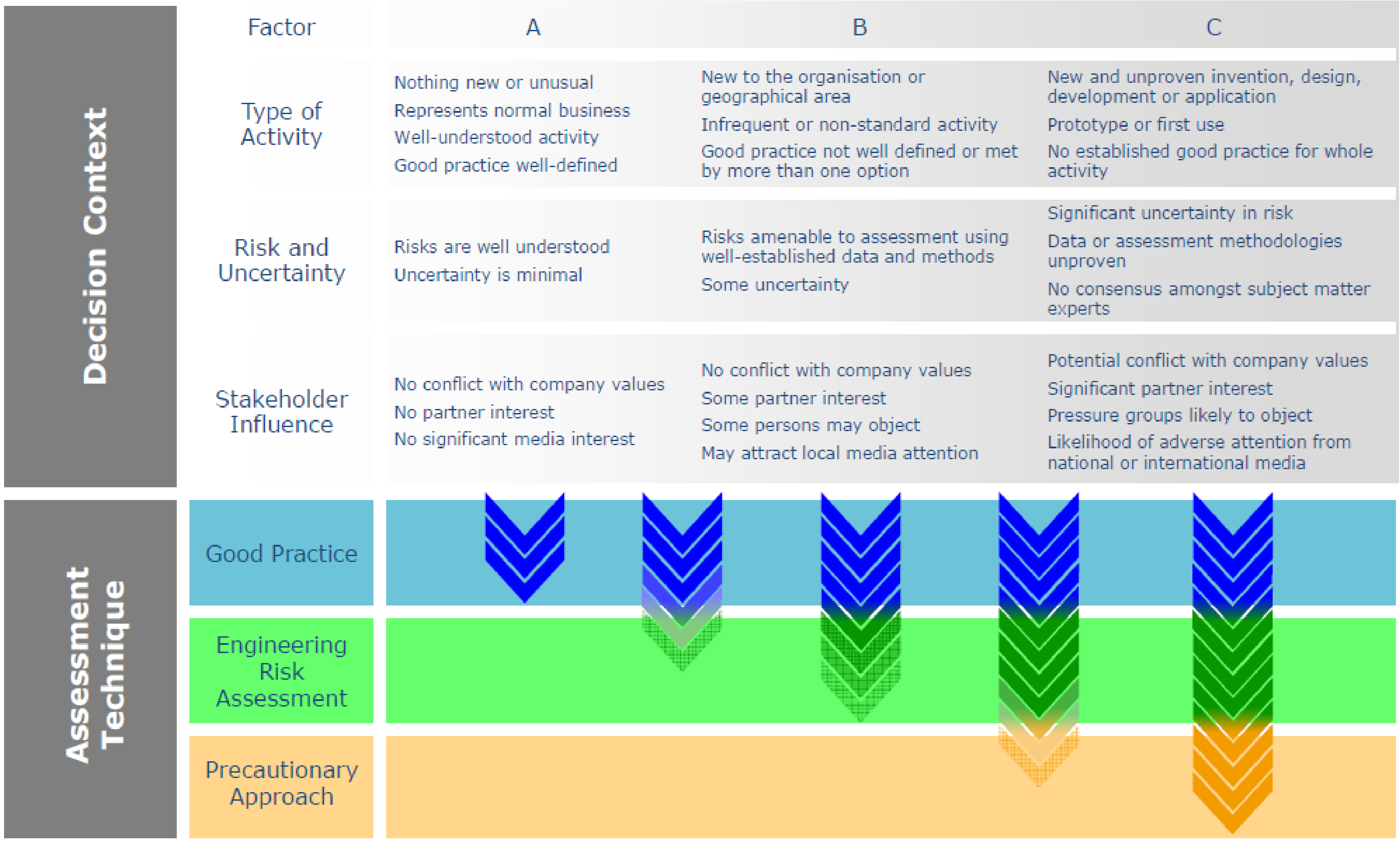
There have been moves in industry towards making decisions based on risk, be it during the design of offshore installations or with regards to fire and explosion management on existing installations.

OGUK have set out a framework for making risk related decisions [7]; this is depicted in Figure 1.

For different decision contexts, the framework diagram suggests the techniques that allow a risk related decision to be made with sufficient certainty:

- For a type A decision, where the risk is relatively well understood, in general the decision will be determined by the application of recognised good practice. In cases where good practice may not be sufficiently well-defined, engineering risk assessment may be required to guide the decision.
- For a type B decision, involving greater uncertainty or complexity, the decision will not be made entirely by established good practice. Thus while any applicable good practice will have to be met, there will also be a need for engineering risk assessment in order to support the decision and ensure that the risk is ALARP.
- A type C decision will typically involve sufficient complexity, uncertainty or stakeholder interest to require a precautionary approach. In this case, relevant good practice will still have to be met and detailed engineering risk assessment will be used to support the decision.

Figure 1: OGUK risk related decision making framework



Decision Context

Factor	A	B	C
Type of Activity	Nothing new or unusual Represents normal business Well-understood activity Good practice well-defined	New to the organisation or geographical area Infrequent or non-standard activity Good practice not well defined or met by more than one option	New and unproven invention, design, development or application Prototype or first use No established good practice for whole activity
Risk and Uncertainty	Risks are well understood Uncertainty is minimal	Risks amenable to assessment using well-established data and methods Some uncertainty	Significant uncertainty in risk Data or assessment methodologies unproven No consensus amongst subject matter experts
Stakeholder Influence	No conflict with company values No partner interest No significant media interest	No conflict with company values Some partner interest Some persons may object May attract local media attention	Potential conflict with company values Significant partner interest Pressure groups likely to object Likelihood of adverse attention from national or international media

Source: OGUK, 'Guidance on Risk Related Decision Making', doc. no. HS088, Issue 2, July 2014

It must be demonstrated for offshore installations in the UK that the risks from all major accidents have been reduced to a level that is ALARP. The HSE defines what is reasonably practicable as follows [8]:

> *In any assessment as to whether risks have been reduced ALARP, measures to reduce risk can be ruled out only if the sacrifice involved in taking them would be grossly disproportionate to the benefits of the risk reduction.*

The sacrifice can be measured in terms of the money, time or effort required to realise the risk benefit. Taken altogether this can also be referred to as the ‘cost’ of implementing the measure. The benefit of the risk reduction is usually measured in terms of the reduction in fatalities and/or injuries. Damage to the environment or assets of the installation can also be assessed in this way; however, the “grossly disproportionate” consideration is not made in these cases.

In reducing risks to ALARP, emphasis should be placed on the primary risk contributors. To this end, it helps if any risk assessment lists the top contributors to risk in terms of the different sections of the process on an installation or the type of event involved (e.g. fire or explosion). However, care should be taken not to miss reasonably practicable ways of reducing the risk from apparently less serious events. Moreover, caution must be taken to avoid ‘reverse ALARP’. Further guidance on this matter is provided in the OGUK guidance on risk related decision making [7].

The HSE advises that where established good practice is available then this needs to be met, or an equivalent measure provided, in all circumstances. However, where established good practice does not exist, is out of date, or the situation is complex and the relevance of individual good practices is questionable, the decision making process on risk reduction action is less straightforward [9]. In such situations cost-benefit analysis (CBA) can be applied to inform decision making.

2.4 Hazard identification and risk assessment

Hazard identification and risk assessment is an integral part of managing fire and explosion risks. ISO 31000 [10], ISO 73 [11] and IEC 31010 [12] discuss risk management, assessment and terminology in general terms applicable across all industries.

Hazard identification and risk assessment in the context of petroleum and natural gas industries, and specifically offshore installations, are discussed in ISO 17776 [13]. The hazard identification and risk assessment process can be summarised as a sequence of three main steps:

> - *Step 1: Identification of the hazard, based upon consideration of factors such as the physical and chemical properties of the fluids being handled, the arrangement of equipment, operating and maintenance procedures and processing conditions. External hazards such as ship collision, extreme environmental conditions, helicopter crash, etc. also need to be considered at this stage.*
> - *Step 2: Assessment of the risk arising from the hazards and consideration of its tolerability to personnel, the facility and the environment. This normally involves the identification of initiating events, identification of possible accident sequences, estimation of the probability of occurrence of accident sequences and assessment of the consequences. The acceptability of the estimated risk must then be judged based upon criteria appropriate to the particular situation.*
> - *Step 3: Elimination or reduction of the risk where this is deemed to be necessary. This involves identifying opportunities to reduce the probability and/or consequence of an accident.*

These steps are described further in the following sections.

2.4.1 Hazard identification

In the offshore oil and gas industry, the majority of hazards are well understood at a high level, often as the result of experience and shared industry knowledge. However, all offshore installations are different and it is a mistake to assume that all hazards will already be known and fully understood; therefore, it is essential to develop a complete understanding of the hazards.

For new installations, it is important to identify hazards as early as possible in the project so that they can be understood, assessed and acted upon as necessary. This will improve safety, reduce costs and minimise impact on the project schedule. The most cost-effective time to eliminate or minimise hazards and risks is at the early stages of the design. In general, the later such issues are tackled, the more difficult and costly any solutions become, and in many cases a late design/construction change can be a magnitude greater in cost than had the feature been incorporated at the design phase. One example of this would be identifying coarse hazard ranges for fire and blast events to inform separation distances for bridge linked platforms. If the separation is later deemed insufficient then the cost of modifying the design or finding other protection means can be high.

Hazard identification is also relevant to existing installations, although it is likely that some measures that may be justified for a new installation are not practical to apply retrospectively for existing installations. In addition, modifications to existing installations may present additional risks that need to be considered. For example, making modifications to pressure containing equipment introduces risks from increased POB, start-up/shutdown risk, breaking containment and the job specific risks such as hot work and working at height.

Further information on hazard identification is provided in Section 2.7.

2.4.2 Risk assessment

With regards to the level of detail of risk assessment, the HSE advises [14]:

> *the risk assessment methodology applied should be efficient (cost-effective) and of sufficient detail to enable the ranking of risks in order, for subsequent consideration of risk reduction. The rigour of assessment should be proportionate to the complexity of the problem and the magnitude of risk.*

So, for example, a simple normally unmanned installation (NUI) which processes low hazard fluids (e.g. heavy crude), with a small hydrocarbon inventory and limited equipment would not require the same level of risk assessment as a large, fully integrated process installation with high pressure/high temperature (HP/HT) and a POB number of 200.

Uncertainty and the Conservative Approach

In assessing risk there is always uncertainty associated with the:

- Complexity of the installation or the decision to be made.
- Assumptions serving as the basis for any assessment.
- Lack of information that might otherwise be used as input to an assessment.
- Use of generic failure rate data in a frequency analysis.
- Availability of suitable techniques or models for the specific circumstances of an installation.

One way to address uncertainty is to use conservative assumptions and methods. A conservative assumption or method will more likely result in an overestimate of risk and thus a more conservative design with more safety measures implemented. In the context of fires and explosions, this covers (but is not limited to):

- Number and strength of ignition sources – more ignition sources will yield a greater probability of ignition thus leading to a higher frequency of fires and/or explosions.
- Weather conditions – there will be less dispersion in calmer wind conditions leading to the formation of larger flammable clouds and thus more severe consequences from fires and explosions (should ignition occur).
- Manning numbers – the more people assumed to be present, and the longer they are present, the greater the possibility they may be impacted by the hazardous consequences.

The level to which the conservative approach is adopted should be in proportion with the level of uncertainty in the assessment and the severity of the consequences of the hazards.

The level of uncertainty in a risk assessment can be difficult to establish, but must be acknowledged. One method is via sensitivity analysis. This is a means of checking the effect of inputs or parameters on the results of the risk assessment. The greater the effect on the results, then the more sensitive the results are to the input or parameter being changed. It is not necessary to subject all inputs and parameters to sensitivity analysis; rather just those with a significant bearing on the particular results related to the decision being made. In the context of fires and explosions, this includes (but is not limited to):

- Time to isolation of a leak and/or blowdown – longer isolation and blowdown times could potentially lead to bigger release volumes thus producing fires and explosions with more severe consequences.
- Ignition probabilities – higher ignition probabilities will produce a higher frequency of fires and explosions.
- Degree of confinement and congestion around equipment (and how this is accounted for in explosion modelling).

It is important to bear in mind that the risk assessment process is not just a one-off, linear process. Rather, risk assessment should be a cyclical process that seeks to maintain risks to ALARP by reconsidering assumptions and approaches in the light of new information and technology.

2.4.3 Risk elimination and reduction

Risk reduction measures range from items of equipment and physical systems through to operational procedures, managerial structures and planning.

The hierarchy of risk reduction measures is explained and summarised by OGUK [7]:

> *Even if the risk reduction achieved by different measures is the same, there is a preference given to hazard avoidance and prevention compared to control and mitigation. This leads to a hierarchy of risk reduction measures (in decreasing order of preference) as follows:*
>
> - *Elimination and minimisation of hazards by design (i.e. inherently safer design);*
> - *Prevention (reduction of likelihood);*
> - *Detection and control (limitation of scale, intensity and duration);*
> - *Mitigation of consequences (protection from effects); and*
> - *Evacuation, escape and rescue (EER) arrangements.*

It is likely that a combination of these measures will be used to manage any given hazard, although inherently safer design (ISD) is commonly accepted as the most effective means of reducing risk. Examples of risk reduction measures are given in Section 8.6.

2.5 Principles of inherently safer design

ISD is an approach to hazard management that emphasises avoiding or limiting the hazard at source, rather than relying on 'add-on' safety features or management systems and procedures to control them [15]. Inherently safer design is generally both intrinsic to and inseparable from the design.

There is always the potential for safety systems to be damaged in a hazardous event. ISD aims to minimise this potential by focussing on prevention rather than protection, and the preference for robust passive protection over active systems.

It is particularly important to follow ISD principles where the consequences of process release or system failure are high. Reliance on engineered (active or passive) safety systems or operational procedures should be reduced where possible. In addition, ISD reduces complexity and reduces the requirement for human intervention, thus resulting in a simpler and more robust system.

2.5.1 Application of inherently safer design

ISD commonly involves implementing some of the following measures [16]:

- Reduction – reducing the hazardous inventories or the frequency or duration of exposure.
- Substitution – substituting hazardous materials with less hazardous ones.
- Attenuation – using the hazardous materials or processes in a way that limits their hazard potential, e.g. storage at lower temperature or pressure.
- Simplification – making the plant and process simpler to design, build and operate hence less prone to equipment or control failure and human error.

Table 1 provides some examples of inherently safer design measures applicable to fire and explosion prevention for offshore installations, and some processes that can be used to achieve the goals of ISD.

ISD should be applied throughout the project duration and continue throughout the life of the installation, although it offers the greatest advantages when applied at the concept selection and definition phase. As the project proceeds, it becomes less feasible and/or less cost effective to introduce inherently safer design.

Generally speaking, at the front-end engineering design (FEED) phase the layout should be designed with the intention of reducing the severity and consequences of major hazards (e.g. by reducing congestion thereby reducing peak overpressures from explosions, or by providing physical separation to minimise escalations and impairment of the TR). At the detailed engineering phase the prevention measures (e.g. gas detection, isolation, blowdown) and mitigation measures (e.g. deluge curtains, firewater monitors) should be designed to reduce the likelihood and severity of major accidents should they occur.

Table 1: Examples of inherently safer design features implemented on installations

Safety Goal	Inherently Safer Design
Benefits of good layout (including partitioning effects or not)	• Place equipment, utilities and personnel areas along a clear hazard gradient • Where possible use as much segregation as possible to limit escalation • Avoid congestion in process areas • Place safety critical equipment in uncongested areas where possible (limits vulnerability to high explosion loads) • Use height between floors to provide ventilation space (cheap volume) • Identify measures required by fire and explosions and balance benefits from measures for each hazard category
Minimisation of potential leak sources/release potential	• Minimise number of pipe joints • Maximise welded pipe joints • Maximise containment integrity • Minimise invasive instrumentation • Eliminate/minimise small bore pipework • Minimise offshore processing and process complexity • Minimise vibration • Design to withstand and facilitate management and assessment of corrosion/erosion
Minimisation of ignition potential	• Ensure there are no naked flames in live plant • Insulate hot surfaces (where inspection is not critical) • Design with effective earth bonding • Use equipment appropriate for hazardous area classification
Minimisation of POB exposure to fire effects	• Separate quarters and non-operational personnel from process areas • Minimise maintenance requirements • Remote operation of processes • Introduce separate accommodation platforms • Use of appropriate fire barriers • Provide multiple escape routes from each hazardous area • Introduce structural redundancy

Safety Goal	Inherently Safer Design
Minimisation of hazardous inventory	• Simplification/minimisation of offshore processing • Use of small isolatable inventories • Effect isolation from large inventories upon gas/leak detection
Minimisation of potential release mass and severity of consequences	• Minimise hazardous inventory • Minimise inventory pressure • Minimise module size • Segregation of release sites from ignition sources and personnel – compartmentalization • Minimise congestion and the possibility of obstructed fires • Improve natural ventilation (to reduce ignition probability, avoid recirculation and external flaming) • Consider the use of subsea completions • Minimise volumes of explosion (may conflict with minimisation of congestion and confinement below). • Consider the potential for missiles caused by explosion during design, and minimise the missiles available in explosion potential areas.
Minimisation of congestion	• Simplify and optimise designs to reduce congestion • Optimise module layout • Segregation of congestion and explosion leak sources
Minimisation of confinement	• Grated decks (reduces confinement but also can reduce segregation) • Open sided modules • Blowout panels/louvres • Confinement consideration during layout of equipment
Maximisation of ventilation	• Platform orientation to make maximum use of prevailing wind direction • Equipment layout to avoid 'dead spots' • Platform aspect ratio to maximise ventilation
Limitation of potential flame front length	• Limit module size • Minimise offshore processing • Add partitions to limit maximum dimensions • Review of aspect ratio of module dimensions

Safety Goal	Inherently Safer Design
Monitoring and maintenance of safety and environmentally critical equipment (SECE) integrity/functionality	• Minimise the exposure of the TR and SECEs to smoke and heat, e.g. separation, passive fire protection (PFP), etc. • Improve SECEs resistance to thermal effects • Protect SECEs from severe vibration effects • Protect SECEs from structural displacement effects • Reduce the requirement for SECEs where possible
Maintain effective management of residual risk	• Use passive systems of control and mitigation in preference to active systems • Use preventative measures where possible rather than mitigation measures • Reduce reliance on personnel to prevent, control or mitigate hazards

2.5.2 Constraints and limitations of inherently safer design

There may be some conflict between measures implemented to improve inherent safety. The relative pros and cons of any inherently safer design measure should be weighed up before making a decision. Some examples of such conflicts are:

- Increased compartmentalisation will generally reduce the size of a potential ignitable gas cloud and the number of potential ignition sources. However, this may decrease the potential for natural ventilation, increase confinement and give rise to obstructions or ventilation limited fires.
- Insulation of hot pipework is one means of eliminating potential ignition sources. However, corrosion under insulation is a major cause of line failure and high operational cost, so this must also be considered.
- Minimisation of equipment may reduce potential leak sources and simplify the process, but this will also lead to less redundancy/availability. This has safety implications, for instance duplication may reduce the number of maintenance interventions required and minimise process interruptions should equipment malfunction. Economic requirements may also make such duplication necessary.
- Whilst it is generally beneficial to reduce in-line instrumentation, instrumentation associated with autonomous systems such as deluge and leak detection systems should not contribute to the likelihood of a release and hence this instrumentation is bound to be beneficial, unless the maintenance requirements and consequences of instrumentation failure increase the risk. Therefore, ISD when applied to such instrumentation may, in some circumstances, increase the overall risk.

2.6 Good practice codes and standards

OGUK uses the following definition of good practice [7]:

> *The recognised risk management practices and measures that are used by competent organisations to manage well-understood hazards arising from their activities.*

Good practice may change over time, or because of increased knowledge about the hazard and/or a change in the acceptability of the level of risk control achieved by existing good practice. Operators should consider if implementing any new good practice is reasonably practicable when applied to their installation. This is because it may not always be practicable to apply retrospectively measures that may be justified for a new installation.

Whilst there are too many examples of good practice to be fully detailed in this document, there are published references that describe good practice. An example is the HSE guidance for the topic assessment of the MAH aspects of safety cases (GASCET) [17], which lists good practice and standards in relation to topics such as structural integrity, fires and explosions, emergency response and decommissioning.

Good practice for specific issues relating to hazard management on offshore installations is available on the HSE OSDR website [18]. This includes various publications [19] including operations notices [20], safety alerts and notices [21], and offshore information sheets (OIS) [22].

With regards to good practice and design, there are two main approaches: prescriptive and performance based. These approaches have their own uses in different situations, which are discussed further in the following sections.

2.6.1 Prescriptive design

The prescriptive approach to design is often employed because of the need to comply with regulations, insurance requirements, industry practices, or company procedures. Whilst a prescriptive approach is reasonable where the design of an installation contains nothing new or unusual, and the hazards are well understood, its limitations should be fully appreciated. This is especially so when applied to more complex designs or where the risks are high. Good practice may not account for the specific circumstances of an installation (e.g. size/configuration, inventories of hazardous substances, process conditions, POB, local conditions, etc.).

2.6.2 Performance based design

Alternatively, performance based design sets goals in terms of the desired level of safety performance. Performance based design is more flexible than prescriptive design, and as such can result in significant cost savings by comparison (except perhaps for smaller projects). Performance based design requires operators to identify, analyse and respond to hazards, thus taking ownership of the hazards, control measures and management of risk. However, performance based design must still consider good practice guidance where relevant and appropriate, and care must be taken not to overlook continuous improvement.

It is performance based design, and the goal setting approach it involves, that is embedded in the regulatory framework in relation to MAHs and offshore installations in the UK.

2.7 Hazard identification

The identification of fire and explosion hazardous events is the start point for the rest of the assessment and of the whole hazard management process. It should use a structured, systematic and auditable approach that addresses both process and non-process fires and explosions and covers all parts of the installation including pipelines, risers and wells.

The hazard identification process should address all foreseeable fires and explosions and, in particular, those involving releases of hydrocarbons. This process should be fully documented including all of the foreseeable causes of initial release, as these should be addressed when identifying the need for specific prevention measures. A log should be kept of all actions arising from hazard identification studies, reports and project concerns so that they can be formally held in a single database, tracked and eventually closed out, thus ensuring that none are forgotten or ignored. Additionally, it may aid the management of hazards to compile a hazard register listing all hazards (not just MAHs), their cause, and how each is or will be handled.

There are various techniques for hazard identification reported in the literature. A study conducted on behalf of the Health and Safety Laboratory (HSL) [23] identified 40 different techniques.

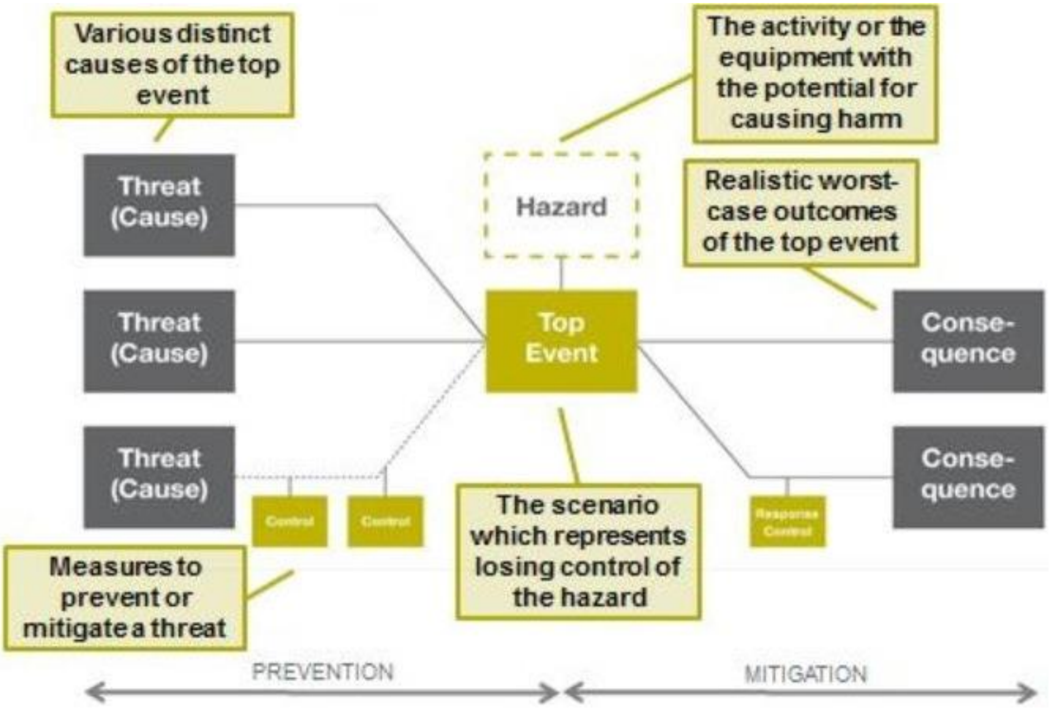
Hazard identification is described in ISO 17776 [13]. The NOPSEMA guidance note on hazard identification is another useful source [24], also Lees' Loss Prevention in the Process Industries [25].

Basic approaches are based solely on hazard checklists, codes and standards, experience and expert judgment. However, where these are inappropriate there are also structured review techniques. These include:

- Hazard identification (HAZID), environmental impact identification (ENVID), and hazard identification and risk assessment (HIRA) studies
- Failure mode and effects analysis (FMEA)
- Hazard and operability review (HAZOP)
- Job hazard analysis (JHA)
- Bowtie analysis (shown in Figure 2)

A more extensive list is provided in Section 2.3 of ISO 17776 [13].

Figure 2: Layout of a bowtie diagram



2.8 Screening of risk

As stated in Section 2.4.2 the rigour with which a risk assessment is carried out should be proportionate to the complexity of the problem and the magnitude of risk. For higher complexity problems with greater perceived risks, more rigorous assessment is justified to provide additional understanding and ensure the residual risk is acceptable. For issues with lower complexity or lower risks, less effort may be required to perform a satisfactory assessment.

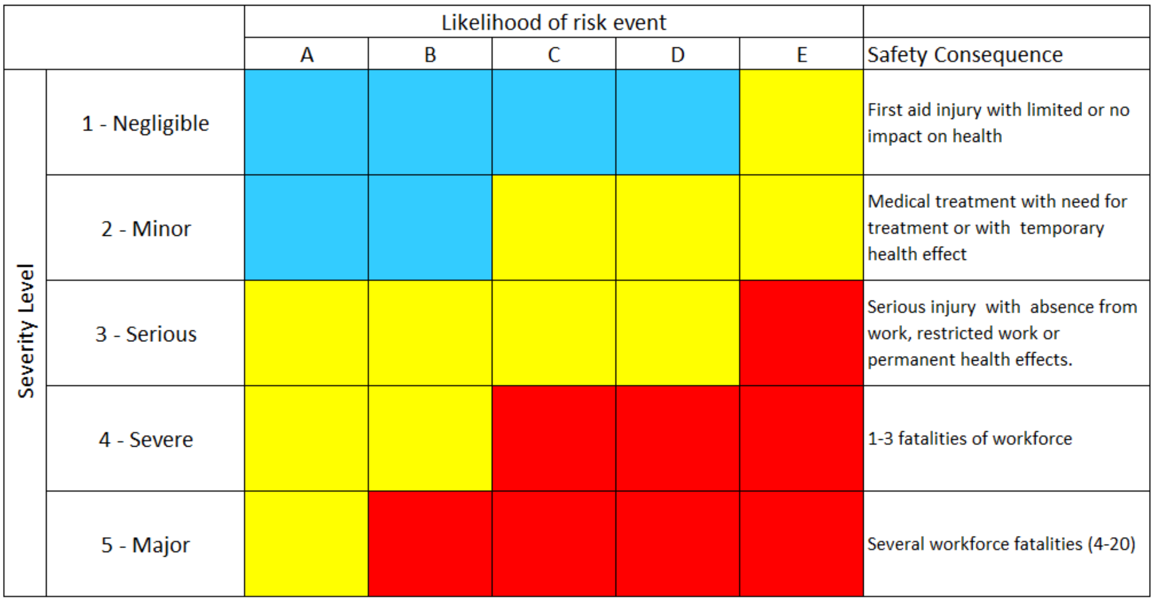
Therefore, it is important to have a means of early estimation of risk to determine the appropriate level of rigour to apply to any subsequent risk assessment(s). Any risk based decisions, be it for modifying an existing installation or designing a new installation, should usually be decided as early as possible. However, detailed analysis may not be feasible early in a project (say due to lack of information); a more qualitative approach is usually more suitable.

A risk matrix provides a simple approach to screening hazards by categorising the consequence and frequency associated with a hazard and equating these to a certain level of risk (as risk is usually taken as the product of consequence and frequency). This way the MAHs can be distinguished from the other hazards, allowing more detailed assessment to be focused on the MAHs, i.e. the hazards with the greatest potential for harm. The other less severe hazards may still be considered but require less rigour, or they may already be covered by other plans and/or procedures in the SMS.

For coarse screening of hazards (e.g. those identified in a HAZID) a simple 3 × 3 risk matrix of consequence severity versus likelihood can be used (although more complex matrices may also be used). Likelihood is a more appropriate term than frequency where a qualitative assessment is being performed (the term frequency implies that numerical values are available). Likelihood can be based on industry experience of similar past incidents. When screening hazards like this it is normal to consider the worst case consequences without consideration of any safety measures in place (or assuming these fail or are not available).

One example of a 5 × 5 matrix is provided in Figure 3.

Figure 3: Example 5x5 risk matrix



		Likelihood of risk event					
		A	B	C	D	E	Safety Consequence
Severity Level	1 - Negligible	🟦	🟦	🟦	🟦	🟨	First aid injury with limited or no impact on health
	2 - Minor	🟦	🟦	🟨	🟨	🟨	Medical treatment with need for treatment or with temporary health effect
	3 - Serious	🟨	🟨	🟨	🟨	🟥	Serious injury with absence from work, restricted work or permanent health effects.
	4 - Severe	🟨	🟨	🟥	🟥	🟥	1-3 fatalities of workforce
	5 - Major	🟨	🟥	🟥	🟥	🟥	Several workforce fatalities (4-20)

2.9 Selection of the representative design accident events

One of the most important decisions taken in the hazard management process is the selection of hazardous events used to define the upper bound (or envelope) of conditions the control and mitigating systems are designed to. The analysis of these events will give the loading parameters for fires and for explosions as described in Sections 3 and 4. It is possible for low risk installations that the design could be based on standard criteria, with the loads from the actual design events being checked at a later stage and compared to the design load. The characteristics of these loadings need to be defined in sufficient detail so that protection systems can be designed to match them.

As already discussed, it is important for a new design that the selection of accidental loads takes account of the potential consequences of escalation. The design loads, defined by dimensioning accident loads (DALs), should in principle be selected to reduce risks to ALARP. Analysis of these potential hazardous events can be complex, however, and in many cases needs to be iterative.

It is important that the analysis is driven by a clear understanding of the overall safety philosophy and risk tolerability criteria. For example, a common design philosophy is to ensure, as far as is reasonably practicable, a period of an hour prior to major structural collapse and loss of TR integrity. This philosophy should allow controlled and orderly evacuation of the facility. This philosophy would define, for example, the survivability of critical structural members.

The level of analysis needs to be appropriate for the type of installation being considered. Different methods of assessment, based on the perceived level of risk, are outlined in the following sections. Means for determining the risk level, such as the risk screening process outlined in Section 2.8 should be considered in conjunction with the risk based decision making approach outlined in Section 2.3. This guidance considers in particular the risk to human life.

2.9.1 Low risk installations

Low risk installations refer to installations such as wellhead platforms that are not normally manned. These have risk profiles characterised by low likelihoods and/or consequences. Qualitatively, it is clear that there are a number of factors that result in the installation being 'low risk' including:

- Low equipment count with a consequential low release frequency.
- Low degree of confinement and process congestion, resulting in little potential for the generation of damaging explosion pressures.
- Less potential for personnel to be harmed on a NUI compared to a permanently manned installation.

An acceptable means of assessment for low risk installations is comparison with specific past cases. Such comparisons should be supported by evidence that a structured assessment has been undertaken to identify areas of difference and that the original means of calculation were sound.

The nomination of a typical installation to represent a fleet of platforms with a broadly similar configuration is acceptable.

2.9.2 Medium risk installations

Medium risk installations cover a variety of different risk profiles, ranging from high consequences with low likelihood, to low consequences with high likelihood. In order to confidently describe an installation as medium risk it is likely that it needs to have strong correlations with existing installations that have well understood risks. Once again, the consideration of risk is focussed on the potential exposure of people to the hazard.

Some examples of features that may result in a medium risk installation include:

- High degree of separation, commonly using multiple bridge linked platforms to ensure that personnel are not exposed to the highest consequence hazards (e.g. minimal manning of a separate wellhead platform), and to reduce personnel exposure to the other hazards (e.g. separating the accommodation from the production facilities).
- Lower pressures than those seen in high risk installations, particularly towards the end of life when the formation and wells are well understood.
- Heavy oil or fluids with high water cut, where the potential for ignition is very low.

Where valid nominal consequences (e.g. overpressures) are available or past cases exist that are relevant, these values may be employed. However, the premise is that the variables listed should be more closely analysed than might be the case for low risk installations, and care should be taken when extrapolating from data.

Where no nominal consequence has been defined for the installation and there are no suitable past cases for comparison, then the level of analysis appropriate for high risk installations (see Section 2.9.3) should be applied.

Some medium risk methods can substitute for some of the tasks defined in the high risk method. The philosophy recommended in this guidance is that, for medium risk installations, the choice of method for any particular task must be justified where it deviates from the high risk method.

2.9.3 High risk installations

The high risk category would include installations with one or more to the following characteristics:

- Large footprint with a significant amount of topside processing, particularly with a layout not previously used.
- High pressure fluids, including significant quantities of produced gas.
- Compression of significant quantities of gas for export, reinjection or gas lift.
- Significant permanent manning level.

It is not unusual for all of these factors to arise together in new offshore production facilities given that many involve development of deepwater fields.

Where the potential risk level on an installation or within a compartment is high, this will warrant a proportionally high level of analysis. The ability of the installation to withstand explosion will need to be determined with a reasonably high degree of rigour as any underestimate could have a significant risk impact. Sensitivity analysis can play an important role in such cases.

This level of analysis would involve:

- Complete set of explosion scenario investigations.
- Combination of computational fluid dynamics (CFD) and phenomenological dispersion, fire and explosion simulations with knowledge of the frequencies of release and ignition.
- Determination of equivalent stoichiometric cloud size.
- Combination of CFD and phenomenological explosion simulation with generation of exceedance curves representing frequency of overpressure exceedance.
- Determination and assessment of the structure and safety and environmentally critical elements (SECEs) against the strength level blast (SLB) and ductility level blast (DLB) design explosion loads (see Section 7).
- Time dependent and possibly non-linear dynamic modelling of the installation and systems response.
- Explicit consideration of escalation and interaction between fire and explosion scenarios including the collapse of tall structures and external explosion.
- Consideration of strong shock and missile generation by the explosion.

2.10 Understanding the fire and explosion hazards

Understanding fire and explosion hazards is the key to their minimisation risks. This applies at all levels of an organisation from the directors to those designing and operating the facilities. This knowledge should be used to inform people making critical decisions in both design and operation. In other words, the knowledge should be used proactively to reduce risk.

Generally speaking, the consequences of fires will depend on:

- Flame intensity – that is heat flux (or surface emissive power, SEP) and flame temperature, which depend (amongst other things) on the hydrocarbon being combusted and the availability of oxygen (for complete combustion).
- Fire duration – the loadings on equipment impacted by fires will depend on the fire duration and intensity, so less intense fires with longer durations can produce similar loadings to more intense fires with shorter durations.
- Availability and effectiveness of mitigation measures – these may include firewater deluge/monitors, foam deluge/monitors.
- Heat load and thermal dose for personnel safety and escape, the integrity of equipment and supporting structure.
- Effects of smoke (thermal radiation, obscuration of escape routes, toxic inhalation).

The overpressure caused by an explosion will depend upon:

- Hydrocarbon gas or gas mixture present.
- Cloud volume and concentration.
- Ignition source type and location.
- Confinement or venting surrounding the gas cloud.
- Congestion or obstacles within the cloud (size, shape, number, location).
- Cloud density
- Cloud non-homogeneity.
- Ignition timing.

Brief descriptions of fire and explosion events are provided in the following sections. More detailed information on fires and explosions is provided in Sections 3 and 4.

2.10.1 Jet and spray fires

Jet fires result from ignited continuous releases of pressurised flammable gas. Spray fires may occur for ignited releases of flammable liquids under high pressure, where the high velocity of release results in a spray. The momentum of the release carries the material forwards in a long plume entraining air to give a flammable mixture. Jet fires and spray fires have high flame temperatures and can produce very high intensity thermal radiation. The high temperatures pose a hazard not only from direct effects of heat on human beings, but also from the possibility of event escalation. For instance, if a jet flame impinges upon a target such as a vessel, pipe or structural member, it could cause an unprotected target to fail within a few minutes.

2.10.2 Pool fires

If a liquid release has time to form a pool and is then ignited before the pool evaporates, then a pool fire results. Because they are less well aerated, pool fires tend to have lower flame temperatures and produce lower levels of thermal radiation than jet fires, but can produce more soot (due to incomplete combustion). Although a pool fire can still lead to structural failure of items within the flame, this will take several times longer than in a jet fire. An additional hazard of pool fires is their ability to move. A burning liquid pool can spread along a horizontal surface or run down a vertical surface to give a running fire.

2.10.3 Flash fires

If a gas release is not immediately ignited then a vapour cloud may form. If the vapour is unconfined and is less dense than air then it will disperse upwards (as will be the case with many natural gas releases). However, a cloud that is denser than air, such as a butane release, will slump and will move downwind at deck level. Any unconfined flammable vapour cloud that is ignited will burn very rapidly with a sudden flash, the combustion of the cloud typically completing in a few seconds. If the source of material that created the cloud (gas release) is still present then the fire will flash back to the source giving a jet fire or pool fire (depending on the nature of the release).

The main aim in modelling flash fires is to estimate the size of the vapour cloud. Inside the cloud, direct contact with the burning vapours will cause fatalities, but the short duration of the fire means that thermal radiation effects are not usually significant outside the cloud. When considering the effects of flash fires it is often anticipated that only superficial damage will be sustained to most equipment, e.g. paint burning away or charring of unprotected cabling.

2.10.4 Fireballs

Immediate ignition of releases, following catastrophic failure of a vessel or full bore rupture of a pipe containing a flammable gas or a superheated liquid, may result in a fireball. With regard to gases, leaks are more likely to result in a jet fire. Fireballs have very high thermal radiation, similar to jet fires, although the duration of the event is short (so for escalation events jet fires generally have more severe consequences than fireballs).

2.10.5 Boiling liquid expanding vapour explosion

If a flame from a jet fire or pool fire impinges on a pressurised vessel containing a flammable liquid then the steel of the vessel wall will become hot. This heat will be transferred to the liquid, which may start to boil, venting vapours through the relief valve. If the flame remains in contact with a part of the vessel containing liquid then the heat is transferred into the liquid and is dissipated through the effect of boiling, preventing the steel from overheating to the point of failure. However, if the flame is in contact with the vessel alongside the vapour space, then the steel will rapidly overheat and fail, causing a sudden release of the material in the vessel. This liquid will then ignite to form a large fireball rising up over the vessel and producing high levels of thermal radiation. This event is called a boiling liquid expanding vapour explosion (BLEVE). In addition to heat, a BLEVE will also generate high velocity missiles from the fragments of pressure vessel and may generate overpressure due to rapid flashing of the liquid. The greatest BLEVE danger arises when a jet fire impinges on a vessel; in this situation, a BLEVE may occur within a few minutes.

2.10.6 Explosion

Under certain circumstances, the delayed ignition of a vapour cloud can result in the generation of pressure as well as the heat produced by the combustion of the vapour. Pressure generation can occur because of the confinement of the vapour cloud or acceleration of the flame to high speeds (or a combination of both of these factors). Pressure generation by flame acceleration leads to a vapour cloud explosion (VCE). Flame acceleration is generally caused by interaction of the explosion with process congestion and would be described technically as a 'deflagration'. However, if the flame front travels fast enough there is the possibility of the deflagration undergoing a transition to a 'detonation', involving very severe overpressures and the pressure development would no longer rely on interaction with process congestion. This is referred to as a deflagration to detonation transition (DDT). Most VCEs offshore would fall into the category of deflagrations.

Effects on people may be primary, secondary or tertiary. Primary effects are injury to the body because of the pressure change (overpressure). Secondary effects are injury because of fragments or debris produced by the overpressure impacting on the body, e.g. due to building collapse. Tertiary effects are injury because of the body being thrown by the explosion and impacting on stationary objects or structures.

An important aspect of an explosion is that it can result in damage to a facility that escalates the original release into a scenario where there may be multiple releases and fires taking place before there has been any opportunity to blowdown the process systems. The potential for this to be combined with damage to safety critical equipment can result in some of the most hazardous situations for the workforce. One of the primary objectives of the design process is to reduce the potential for such escalation as far as reasonably practicable.

2.10.7 Sources of guidance

Some examples of further guidance on hazards, fire and explosion assessment to support this document are listed below:

- HSE Offshore Information Sheets (OIS) [22]
- CMPT Guide to Risk Assessment for Offshore Installations [26]
- OGP Risk Assessment Data Directory [27]
- TNO Coloured Books [28]
- Lees' Loss Prevention in the Process Industries [25]

2.11 Consideration of escalation

In addition to considering the effects of an initial fire or explosion, it is important that a structured approach is taken to determine whether and how an event can escalate to endanger personnel. This also allows identification of all the subsequent failures that would have to occur before personnel who are not affected in the initial event are put at risk. Escalation analysis is not normally carried out in isolation, but rather should be included as part of fire and explosion assessment.

The primary objectives of the escalation analysis are to:

- Identify mechanisms whereby an initial event may escalate to impinge on key systems or facilities, e.g. the TR and/or evacuation and escape facilities.
- Identify where control or mitigating measures could be used to prevent, delay or reduce escalation or protect life.
- Identify the combination of measures needed to deal with each major hazardous event and to provide an input to the development of associated performance standards.
- Evaluate the effects on the installation safety systems at each stage of escalation and how this may affect subsequent escalation.
- Evaluate the probability and hence the frequency of each escalation path which affects the key facilities or systems such as the TR and EER facilities and the time duration from the initial event.

This may be carried out as an event tree analysis. This can show the sequence of failures which need to occur to result in a particular level of consequence and give designers and the operator/owner the opportunity to add, to or enhance the safety systems to break the sequence of events.

Experience has shown that often only a relatively small number of escalating scenarios contribute significantly to the major accident risk on an installation. Therefore, the escalation analysis is an important aspect of hazard assessment and risk management. It is important that the location, frequency, timing and duration of different scenarios are fully considered so that mechanisms and routes by which a fire or explosion could escalate to cause ‘critical failure’ can be identified.

Input data from the previous steps of the assessment include the:

- Location and description of the initial event especially its size, severity, duration and frequency.
- Means by which the initial event may escalate and, at each escalation stage, the corresponding probability and time to escalation.
- Effects of the events on the installation including the safety systems at each stage of escalation and how this affects subsequent event progression.
- Contribution of safety systems to reducing the consequences and the probability of their successful operation.
- Effects on the key facilities or systems such as the TR and EER facilities in terms of impairment, time to impairment and impairment frequency.

It is possible that systems may fail to operate successfully or could be damaged because of a fire or explosion incident. An emergency systems survivability analysis (ESSA) is commonly carried out to identify what the impact of all credible scenarios are on critical systems, and ensure that these systems are adequately protected to be available on demand. It is worth noting that not all systems will be required in all incidents, and care should be taken to ensure that the survivability requirements are aligned with potential scenarios.

It may also be necessary to consider the actions and decisions of key personnel, in particular the Offshore Installation Manager (OIM) in responding to an escalating situation. The decision to move personnel to different parts of the installation, to abandon the installation, to fight the fire, etc. and the time at which these decisions are made can have major implications for the outcomes.

2.12 Lifecycle factors

The main factors affecting fire and explosion hazards (and their management) throughout the installation lifecycle are summarised in Table 2.

Table 2: Summary of lifecycle factors

Project Phase	Factors Affecting Fire and Explosion Hazards and Risks
Concept Selection	• Offshore processing content (amount of equipment and potential leak and ignition sources) • Offshore structure type • Location of living quarters • Equipment layout • Decks plated or grated • Operation and manning philosophy (exposure of personnel to fire and explosion risk)
FEED	• Philosophy for engineering, piping, etc. • Deck sizing • Nominal explosion loading • Fire area sizing, firewall blast wall location • Determination of constructability • SECE categorisation – identification of high criticality items
Detailed Design	• Design for overpressures, dynamic pressures • Finer points of layout • Changes to ensure constructability • Firewater and vent piping, location and schedule • Supports for SECEs determined • Control systems designed • Verification of constructability • Assembly/writing of maintenance and inspection procedures • Escape, Evacuation and Rescue • Deluge • Hazardous area classification
Installation/Commissioning	• Small bore piping • Competence of construction assured • Completions and hydrocarbon integrity checks

Project Phase	Factors Affecting Fire and Explosion Hazards and Risks
Operation	• Early operations: – Start-up – Maintenance – Verification • Mid-life: – Management of Change – Changing process conditions – Combined Operations (COMOPS) – Brownfield projects – New knowledge (e.g. new understanding of hazards) • Late-life and life extension: – Degradation – Obsolescence – Commercial constraints – Depletion and increased water cut • Decommissioning Programme – Assembly of decommissioning procedures and assurance of integrity during decommissioning
Decommissioning	• Implementation of decommissioning procedures • Management of Change • Process of isolation from hydrocarbon sources

These lifecycle factors are discussed in more detail in Sections 8.3 and 8.8. However, it should be noted that the most significant project decisions with respect to MAHs are often taken during the concept selection phase. The majority of these decisions have a substantial influence on the hazards that must ultimately be addressed by the engineering work and subsequently during the operational phase of the project. The following points should be considered:

- Maximum safety leverage is available during the concept selection and definition phases.
- Assessment carried out during the concept selection and definition phases is significantly more cost effective than during the later phases.
- As designs become more developed in the later stages they can also become less flexible, and fewer options are available to implement safety features.

Refer to section 8.4 on inherently safer design for more information on inherently safer design.

3 Derivation of fire loadings and heat transfer

3.1 Introduction

In the following sections, generic types of fire that might occur on or near an offshore installation are discussed. The fire types are considered further in terms of their flame characteristics and how their behaviour might be affected by confinement and/or deluge. The parameters used to define the fire and the hazards presented by the fire in terms of thermal and smoke loading are also summarised. Much of this data is based on measurements taken in large-scale experimental studies.

Also considered are the effects of deluge on the potential heat loads from fires and the effect on the temperature rise of an engulfed object, plus the manner in which passive fire protection (PFP) may limit the rate of temperature rise of an engulfed object and how blowdown may reduce the likelihood of failure of vessels.

The information provided on fires is largely qualitative. Further theoretical details on fires and modelling can be found in FABIG Technical Note 11 [1].

3.2 Fire characteristics and combustion effects

3.2.1 General

The nature of the flame and the thermal loading it may present to the surroundings are described in the following section for different fire types. Where appropriate, the effect of confinement or water deluge on the fire is discussed.

3.2.2 Gas jet fire

3.2.2.1 Nature of gas jet fires

An ignited pressurised release of a gaseous material (most typically natural gas) will give rise to a jet fire. A jet fire is a turbulent diffusion flame produced by the combustion of a continuous release of fuel. Except in the case of extreme confinement, which might give rise to extinguishment, the combustion rate will be directly related to the mass release rate of the fuel.

In the offshore context, the high pressures mean that the flow of an accidental release into the atmosphere will be choked having a velocity on release equal to the local speed of sound in the fluid. Following an expansion region downstream of the exit the flame itself commences in a region of subsonic velocities as a blue relatively non-luminous flame. Further air entrainment and expansion of the jet then occurs producing the main body of the jet fire as turbulent and yellow. In the absence of impact onto an object, these fires are characteristically long and thin and highly directional. The high velocities within the released gas mean that they are relatively unaffected by the prevailing wind conditions except towards the tail of the fire. The fire size is predominantly related to the mass release rate which in turn is related to the size of the leak (hole diameter) and the pressure (which will most likely vary with time as a result of system isolation and blowdown).

In the case of high pressure releases of natural gas, the mixing and combustion is relatively efficient resulting in little soot (carbon) formation except for extremely large release rates. Hence little or no smoke is produced by natural gas jet fires (typically <0.01 g m^{-3}), and the fires tend to be less luminous than jet fires involving higher hydrocarbons. CO concentrations in the region of 5 to 7% v/v have been measured within a jet fire itself but this is expected to drop to less than 0.1% v/v by the end of the flame.

Figure 4 shows examples of natural gas jet fires impinging on a pipe obstacle.

Figure 4: Natural gas jet fires impinging on a pipe

Source: Picture courtesy of DNV GL Spadeadam Testing & Research

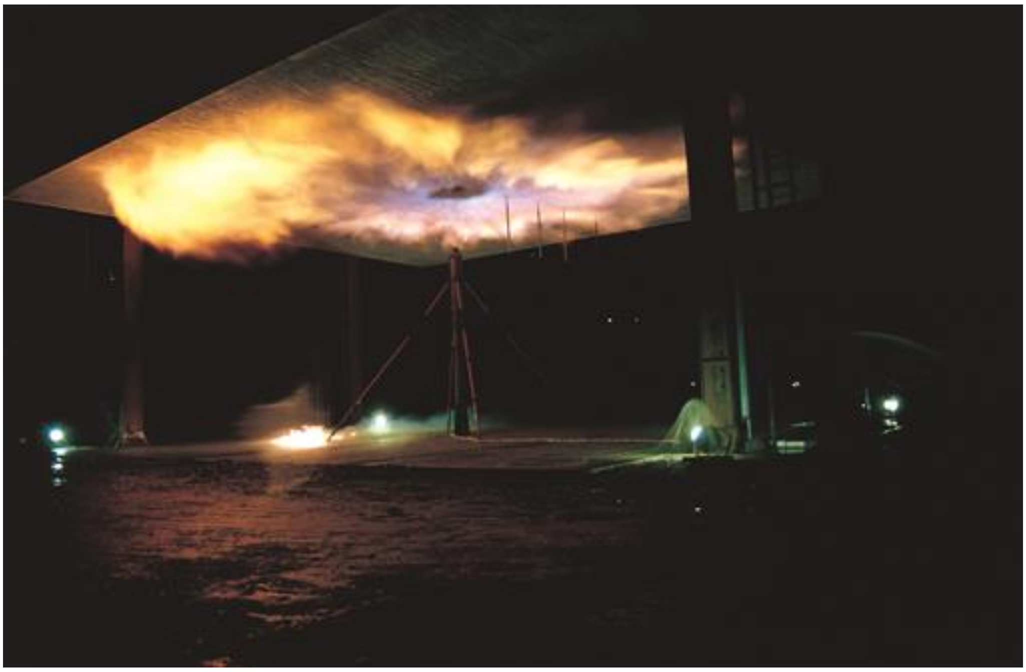
A factor that is often overlooked is the noise produced by sonic gaseous releases. This is usually high-pitched and so loud that it may prevent effective radio communication between personnel. As a result, emergency actions could be hampered.

A further point to note is that some combinations of leak size and pressure will not give rise to an inherently stable flame. For hole sizes under 30 mm diameter, there is a lower bound pressure which high pressure releases must exceed to produce stable flames. Simplistically, this extends approximately linearly from 2 barg at 30 mm diameter to about 75 barg at 8 mm diameter. In practice, this means that most small leaks will be inherently unstable and will not support a flame without some form of flame stabilisation, such as the presence of another fire in the vicinity to provide a permanent pilot or stabilisation as a result of impact onto an object such as pipework, vessels or the surrounding structure.

This implies that unstable flames may self-extinguish and revert to leaks, possibly resulting in an explosion hazard. This aspect of flame behaviour should be considered in determining major hazard scenarios and their escalation paths; however, in the highly congested environment offshore, impact within a short distance is very likely, and small leaks will most likely stabilise on the nearest point of impact.

Apart from providing flame stabilisation, impact onto an obstacle may also significantly modify the shape of a jet fire. Objects that are smaller than the flame half-width at the point of impact are unlikely to modify the shape or length of the flame significantly. However, impact onto a large vessel may significantly shorten the jet fire, and impact onto a wall or roof could transform the jet into a radial ‘wall jet’ where the location and direction of the fire is determined by the surface onto which it impacts. Figure 5 shows a high pressure natural gas jet fire impacting on a roof forming a radial ‘wall jet’.

Figure 5: High pressure natural gas jet fire impacting on a roof



Source: Picture courtesy of DNV GL Spadeadam Testing & Research

As noted above, the combustion process within a natural gas jet fire is relatively efficient and produces little soot (carbon). Consequently, these flames are not as luminous as higher hydrocarbon flames. Radiation emissions from natural gas flames arise mostly from water vapour and carbon dioxide, except for very large releases where soot production starts to enhance the process. The long thin shape may also result in a flame path that is not optically thick. The net result is that the radiative heat transfer to the surroundings is lower than for higher hydrocarbon flames. This is characterised by a reduction in the fraction of heat radiated, *F*, where *F* is the ratio of the total energy radiated by a flame to the amount of combustion energy produced.

Objects engulfed by the flame receive thermal load from the radiation produced by the flame and also the heat transferred by motion of the hot gases in the jet. These are termed radiative and convective heat transfer respectively. The radiative heat transfer is generally lower for natural gas jet fires compared to those involving higher hydrocarbons, but the high velocities within natural gas jet fires can result in higher convective heat transfer to objects.

Clearly, the total heat flux imparted to an engulfed object will vary over the surface of the object. In addition, the relative proportions of convective and radiative heat flux will vary over the surface, with the highest convective component likely to be experienced close to the point of impact of a flame where the highest velocities occur, whereas the highest radiative heat load will be experienced where the more radiative part of the flame (usually nearer the end of the flame) is viewed by the object. As the more radiative part of the flame is closer to the tail, this can result in the highest overall heat fluxes being experienced on the rear surface of an engulfed object, which may seem counter-intuitive.

Neglecting such spatial variations, broadly speaking, for a given location of an object within a flame (as a proportion of flame length), the convective component is more or less constant with increasing size of release. The radiative component increases with release rate as the flame has a greater length and width and the additional total amount of combustion along any line of sight through the flame adds to the radiation being emitted from the surface. This increase in the radiative component continues until the flame becomes optically thick, where further increase in the flame size does not increase the radiative component. This can also coincide with the flame becoming smokier and the relative proportion of convective to radiative flux, therefore, varies with fire size.

3.2.2.2 Effect of deluge on gas jet fires

The activation of general area deluge can adversely affect the stability of high pressure gas jet fires, particularly if the fire is not impacting onto an obstacle. However, in most practical cases, this undesirable effect is very unlikely to occur, as impact onto obstacles will provide adequate flame stabilisation. Indeed, deluge has little effect on the size, shape and thermal characteristics of a high pressure gas jet fire. Therefore, the heat loading to engulfed obstacles is not diminished. The same is true for dedicated vessel deluge systems; the water being unable to form a film over the vessel in the presence of the high velocity jet, and so dry patches form where the temperature rise in this area is undiminished by the action of deluge, though there will be cooling provided to a vessel and its contents outside the area of impact.

There is some evidence that the deluge increases combustion efficiency resulting in lower CO and increased CO_2 levels within the flame.

The major benefit of area deluge with jet fires arises from the suppression of incident thermal radiation to the surroundings, which protect adjacent plant and aid escape by personnel [2]. For a medium velocity type (e.g. MV57) nozzle operating at 12 $l\ min^{-1}\ m^{-2}$, incident radiation levels can be reduced by about 20% for a single row of nozzles, 30-40% for 2 rows and 40-60% for more than 2 rows (general area deluge). Increased deluge rates can further reduce incident radiation levels: 60-70% at 18 $l\ min^{-1}\ m^{-2}$ and 80-90% at 24 $l\ min^{-1}\ m^{-2}$ for general area deluge. Nozzles producing smaller droplet sizes can have an enhanced mitigation effect, but there is an increased risk that the droplets will be blown away by the wind.

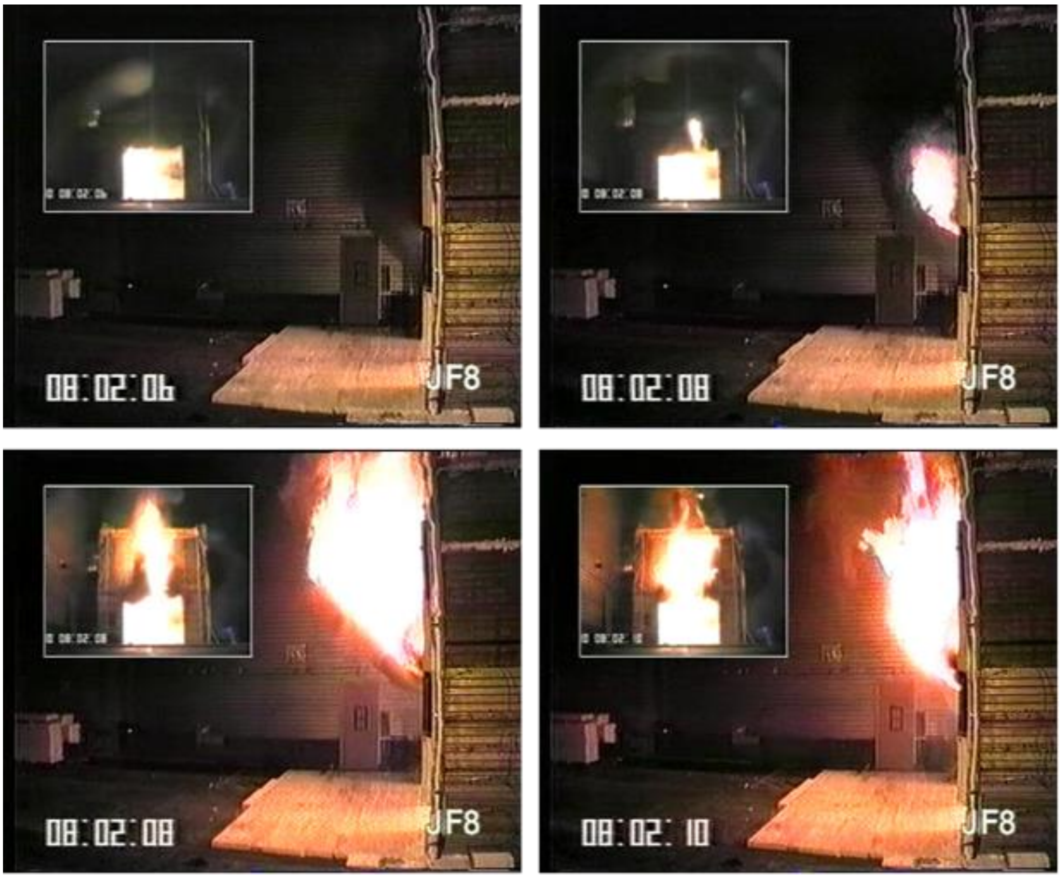
3.2.2.3 Effect of confinement on gas jet fires

The behaviour of a jet fire within a confined or partially confined area will depend upon the degree of confinement and the direction of the jet relative to the ventilation opening. If ventilation is plentiful or the jet is directed through a vent then there may be little difference in jet fire characteristics compared to an unconfined fire. However, if there is limited or no natural ventilation, then a large fire may not be able to entrain enough air for complete combustion inside the compartment. This is likely to result in increased levels of incomplete combustion products such as CO, increased levels of smoke (soot) and increased flame temperatures, particularly in regions close to the ceiling of a compartment where hot combustion products may be trapped and recirculate. This leads to increased heat flux to objects and surfaces compared to an unconfined fire.

The location where combustion occurs and the hottest parts of the flame may also shift due to the confinement. In tests involving horizontal jet fires in a compartment incorporating a single wall vent, where the jet was directed away from the vent [3], increased temperatures were seen at the interface between the smoke layer leaving the compartment and the air layer entering the compartment, most particularly in the area furthest from the vent.

Unlike unconfined fires, the behaviour of under-ventilated confined fires changes with time as the air initially available within the compartment is consumed, and this may lead to 'external flaming' after a period of time when the partially combusted mixture becomes flammable outside the vent, resulting in further combustion. An example of a flame burning into an external smoke plume is shown in Figure 6, which shows a confined jet fire experiment.

Figure 6: External flaming commencing in a confined jet fire experiment



Source: Picture courtesy of Steel Construction Institute, experiment conducted by SINTEF

CO levels of up to 5% v/v at the vent may occur, but after the onset of external combustion the CO levels drop to typically less than 0.5% v/v by the end of the flame. Soot production is related to the equivalence ratio, ϕ, which is defined as:

$$\phi = r\frac{m}{a}$$

where

m is the mass burning rate of fuel

a is the mass rate of air entrained

r is the mass ratio of air to fuel required for stoichiometric burning (~15 for higher hydrocarbons)

Soot production may range from about 0.1 g m^{-3} at an equivalence ratio equal to 1.3 to up to 2.5 g m^{-3} at an equivalence ratio equal to 2.

Certain ventilation patterns could lead to flame instability and extinguishment. The worst case condition is likely to occur if the jet fire is slightly under-ventilated as this leads to high heat release rates and enhanced soot production.

3.2.2.4 Confinement and deluge of gas jet fires

Deluge of a confined jet fire may lead to flame extinguishment, though this may then result in an explosion hazard from the continuing release. The likelihood of flame extinguishment is significantly increased if the surroundings are already hot at the time the deluge is activated as the main mechanism which results in extinguishment of the jet fire is 'inerting', that is evaporation of the water droplets leading to a mixture of gas/air/steam within the compartment which is outside the flammable limits. The water vapour may also contribute to flame instability by reducing the burning velocity. However, if the deluge is activated at an early stage, prior to the compartment walls becoming hot, then the fire may not be extinguished and some benefit in terms of reduced flame temperatures and wall temperatures may accrue.

3.2.2.5 Two-phase jet fire and liquid jet fires

An ignited release of a pressurised liquid/gas mixture (such as 'live crude' or gas dissolved in a liquid) will give rise to a two-phase jet fire [4]. The gas stream atomises the liquid into droplets, which are then evaporated by radiation from the flame. A pressurised release of a liquid can also give rise to a jet fire in which two-phase behaviour is observed if the liquid is able to vaporise quickly. This is most likely to occur when a liquid is released from containment at a temperature above its boiling point at ambient conditions whereupon flash evaporation occurs, (for example condensate with a significant content of propane and butane).

Pressurised releases of non-volatile liquids (for example, kerosene, diesel, or stabilised crude) are unlikely to be able to sustain a two-phase jet fire, unless permanently piloted by an adjacent fire; even so, some liquid dropout is likely and hence the formation of a pool. At high pressures, a spray of liquid droplets may be formed which can drift in ambient winds and become dispersed over a wide area.

As for the gas jet fire described above, the two-phase jet fire is a turbulent diffusion flame produced by the continuous combustion of a fuel at a rate directly related to the mass release rate, producing a fire which is long and thin (although generally wider than a gas only jet fire) and highly directional. The exception is when liquid dropout occurs, leading to a potentially increasing accumulation of fuel as a pool. Two-phase jet fires (particularly those generated by flashing liquid releases) are significantly less noisy than gas jet fires. As for gas jet fires, impact onto an obstacle larger than the flame half-width at the point of impact may shorten or modify the shape of a fire significantly.

The liquid content results in relatively higher mass release rates for a given aperture and pressure compared to gaseous releases. Estimating the release rate is difficult and the output from codes should be viewed with caution, as the modelling can be complex.

The generally lower exit velocities from flashing liquid releases lead to shorter flame lift-offs and proportionately shorter and more buoyant flames overall. The lower velocities also make the fires more wind affected whilst the higher hydrocarbon content of these fuels increases the flame luminosity. However, two-phase releases involving gas dissolved in, or mixed with, a liquid can result in a jet fire that combines the worst aspects of both the gas jet fire and the flashing liquid jet fire, that is, high velocities and high flame luminosity.

Figure 7 shows an example of a propane jet fire, in this case impinging on a vessel. The increased flame luminosity and smoke production are noticeably different from the natural gas jet fires.

Figure 7: Propane jet fire impinging on a vessel

Source: Picture courtesy of DNV GL Spadeadam Testing & Research

The higher hydrocarbon content also results in more soot being formed than in a natural gas jet fire, although there is no available experimental data quantifying the difference. Measurements in the smoke downstream of a 'live crude' jet fire determined an optical obscuration factor of typically 10% over a 200 mm path length. This corresponds to a visibility distance of about 5 m.

The soot produced then contributes significantly to the radiant emissions from the flame, resulting in a proportionately higher contribution of radiative flux to engulfed objects. However, the generally lower velocities arising from flashing liquid releases (such as propane or butane) results in a lower convective flux to engulfed objects. Impact on an obstacle close to the leak can also result in a local cold spot and hence high temperature gradients to the surrounding hot areas, inducing thermal stress.

In the case of a pressurised gas-liquid mixture (such as 'live' crude), the high velocities may still occur and result in a high convective contribution, whilst the higher hydrocarbon content maintains a high radiative contribution; making these type of jet fires a 'worst case' in terms of total heat flux to engulfed obstacles. Experimental work suggests that the maximum combined fluxes occur for gas-liquid mixtures that are about 70% by mass liquid.

Later in a field life, installations may be producing 'live' crude that includes a significant quantity of water. Experiments have shown that mixtures with a 'water cut' (defined as mass of water/mass of fuel × 100%) of up to 125% remain flammable, although not necessarily capable of supporting a stable flame in the absence of some other supporting mechanism. The inclusion of water also slightly increases flame length and flame buoyancy, and the amount of smoke produced reduces significantly. For water cuts under 50% no significant reduction in heat fluxes to engulfed objects can be expected (<10%). However, over 50% the flames are significantly less radiative, and the overall heat flux to an obstacle can be reduced by 40% or more.

3.2.2.6 Effect of deluge on two-phase jet fires

Compared to the situation with a gas jet fire, the use of dedicated vessel deluge to protect a vessel against a flashing liquid two-phase jet fire (e.g. propane, butane) can be more effective. The water interacts with the flame to some extent; reducing the flame luminosity and the amount of smoke produced. Nevertheless, at typical application rates (10 to 15 $l\ min^{-1}\ m^{-2}$) it cannot be relied upon to maintain a water film over the vessel and hence to prevent vessel temperature rise in areas where dry patches form, although the rate of rise may be expected to reduce to 20-70% of the rate without deluge for a propane jet fire. Similar behaviour has been noted for 'live' crude jet fires with dedicated deluge although, in this case, no reduction in the rate of temperature rise was observed in the area where the fire impacted the obstacle. However, in tests with an increased water application of 30 $l\ min^{-1}\ m^{-2}$, a 2 tonne liquefied petroleum gas (LPG) tank was effectively protected when subjected to a 2 $kg\ s^{-1}$ flashing propane jet fire (see Figure 7).

For 'live crude' jet fires, using area deluge at the 'standard' rate of 12 $l\ min^{-1}\ m^{-2}$ is unlikely to modify the flame behaviour although there is some evidence that a higher deluge rate (24 $l\ min^{-1}\ m^{-2}$) can result in water interaction with the flame, resulting in a shorter flame and some reduction in heat fluxes to certain areas of an engulfed object, notably the front (where flame impact occurs) and top areas. Since dedicated vessel deluge is more effective at reducing the radiative heat fluxes in the region to the rear of the vessel, the combination of area deluge and dedicated vessel deluge can be effective in reducing overall heat fluxes to a vessel such that the temperature rise is halted or at least the rate of temperature rise is reduced. This may prevent vessel failure, especially if combined with a blowdown strategy.

As for gas jet fires, a major benefit of area deluge of two-phase jet fires arises from the attenuation of incident thermal radiation to the surroundings, which protect adjacent plant and can aid escape by personnel. Even dedicated vessel deluge alone can result in some reduction (~15-20%) in the incident thermal radiation to the surroundings as a result of modifying the flame characteristics.

Measurements in the combustion products downstream of 'live crude' jet fires determined an obscuration factor due to smoke of typically 10% over a 200 mm path length without deluge and no significant change was noted in the presence of area deluge at 12 $l\ min^{-1}\ m^{-2}$. At 24 $l\ min^{-1}\ m^{-2}$ the smoke changed from black to grey due to the increased water vapour and this had the effect of increasing the obscuration factor to about 20%, corresponding to a visibility distance of about 2 m.

3.2.2.7 Effect of confinement on two-phase jet fires

Confined two-phase jet fires are expected to behave in a similar manner to confined gas jet fires (see Section 3.2.2.3).

3.2.2.8 Confinement and deluge of two-phase jet fires

The effect of area deluge on two-phase jet fires in compartments is expected to be similar to that noted in Section 3.2.2.4 for gas jet fires. Extinguishment could give rise to a mist-air explosion hazard and/or the formation of a liquid pool. In tests involving only partial confinement around the upper area of a module, during which 'dead spaces' occurred close to the ceiling, area deluge was found to be beneficial in reducing heat fluxes to the ceiling surface, reducing the flame extent and the amount of smoke produced.

3.2.3 Pool fires on an installation

3.2.3.1 Nature of hydrocarbon pool fires

A pressurised release of a hydrocarbon liquid which is not sufficiently atomised or volatile to vaporise and form a jet fire will form a pool. Similarly, a spillage from non-pressurised liquid storage will result in a liquid pool being formed. Ignition of the vapours evolving from the liquid can lead to a pool fire that has a turbulent diffusion flame. For hydrocarbons such as condensate, the vapours will evolve readily from a spillage and be easily ignited. For heavier hydrocarbons, such as diesel or crude oil, vapour evolution is not sufficient to produce a flammable vapour air mixture unless the fuel is heated. The temperature at which a fuel produces flammable vapours in air is its 'flash point'.

Ignition of a liquid below its flash point will likely require the presence of other fires in the vicinity providing sufficient energy to initiate vapour evolution. However, once ignited, the fire itself radiates heat to the pool surface causing more fuel to evaporate. The heat transfer from the flame to the pool controls the vapour evolution rate (and hence mass burning rate) and within minutes the fire will reach a steady state condition of flame size and mass burning rate. Larger fires from larger pools will tend to result in higher mass burning rates. However, an upper limit is reached when the radiation to the pool surface is independent of the flame thickness above it (optically thick). This occurs for fires only a few metres in diameter for heavy hydrocarbons due to the radiative emissions from soot. The mass burning rate is also dependent on the fuel type and for liquid hydrocarbons decreases with increasing carbon number (typically ranging from 0.1 kg m^{-2} s^{-1} for light hydrocarbons to 0.05 kg m^{-2} s^{-1} for some crude oils).

Combustion of these relative high hydrocarbons inevitably leads to the production of large quantities of soot, particularly in large pool fires where the size of the pool reduces the ability of air to mix with the fuel evolving in the centre of the pool. Figure 8 shows an example of a pool fire involving heavier hydrocarbons.

Figure 8: Hydrocarbon pool fire

Source: Picture courtesy of DNV GL Spadeadam Testing & Research

The soot emissions result in the characteristic yellow flame and large quantities of smoke can be produced to the extent that the smoke can result in reduced thermal radiation to the surroundings by screening of the radiant flame.

Hence, the fraction of heat radiated, *F* (see Section 3.2.2.1 for definition), tends to decrease with increasing fire size, although the smoke hazard may increase.

In measurements in the smoke downstream of 16 m^2 diesel pool fires, the obscuration factor over a 200 mm path length, as a result of the soot, was found to be typically 30% corresponding to a visibility distance of about 1 to 2 m. CO levels measured at the same location were in the range 100-200 ppm v/v. However, a worst case level at the end of the flame of about 0.5% v/v is recommended. Soot levels in the range 0.5 g m^{-3} to 2.5 g m^{-3} can be expected.

Except in very large fires where buoyancy driven turbulence may become significant, the low velocities within the fire result in the flame being affected by the wind and this factor determines the trajectory of the flame. These low velocities also result in low convective heat fluxes to objects engulfed by the fire; the predominate mode of heat transfer being radiation.

3.2.3.2 Effect of deluge with hydrocarbon pool fires

General area deluge can be very effective in controlling hydrocarbon pool fires and mitigating their consequences. If the water is capable of reaching the liquid pool, the cooling of the fuel reduces vapour evolution and hence reduces the size of the flame. This, in turn, leads to reduced radiative heat transfer from the flame to the fuel surface, which also contributes to reducing the vapour evolution. Consequently, with time, the fire size is reduced and complete extinguishment may result or, if not, sufficient control achieved that manual firefighting could be safely undertaken.

The ability of the water to enter the pool of fuel is higher on the upwind side of the fire where the thickness of the flame is least. Consequently, as the deluge starts to take effect on the fire, the flame retreats from the upwind side of the spillage. In tests involving condensate, the fire coverage of the pool was reduced by over 90% in 10 minutes. Hence, after 10 minutes, the flame size was commensurate with a pool of less than 10% of the original area. The introduction of a small percentage (1%) aqueous film forming foam (AFFF) into the deluge system can significantly increase the rapidity of achieving fire control and extinguishment.

Due to the much reduced fire size when a pool fire is subject to water deluge, the amount of smoke is also significantly reduced. Measurements of the obscuration factor over a 200 mm path length in the combustion products from a diesel pool fire dropped from typically 20-30% to negligible levels when the fire was deluged and CO levels at the same location dropped from over 100 ppm v/v to typically 10 ppm v/v. However, if the water does not directly interact with the fire itself and only interacts with the stream of smoke evolving, then there is no evidence that the water deluge ‘washes’ soot out of the smoke, nor that the toxicity (such as CO level) is reduced. A point of note is that the cooling effect of deluge may reduce the smoke buoyancy and possibly result in smoke being present at lower heights where it may hinder the visibility for personnel trying to escape.

The heat loading to objects engulfed in a pool fire may also be reduced by the activation of deluge, most particularly on the surfaces where a water film can be maintained. The vulnerable areas will be the underside where the water cannot provide coverage and the downwind side where the flame is likely to be thickest. Nevertheless, in these areas the rate of temperature rise is likely to be reduced and additional benefit accrues from the action of the deluge in reducing the fire size. The use of dedicated vessel deluge would be expected to protect an object engulfed in a pool fire, especially in combination with general area deluge that will, simultaneously, reduce the degree of fire attack.

As for jet fires, the water deluge will also provide benefit to objects not engulfed by the fire by attenuating the thermal radiation (see Section 3.2.2.2).

3.2.3.3 Confined hydrocarbon pool fires

The behaviour of confined pool fires will depend on the degree of ventilation and whether the confining structure becomes hot and re-radiates heat to the fire. In the case of adequate ventilation for combustion, the mass burning rate and fire behaviour will be similar to a pool fire in an unconfined area, unless the walls become hot due to insulation in which case the flame temperatures may rise significantly (by about 200-400°C) and hence the heat fluxes to objects within and near the flame will rise. This is associated with soot combustion and can lead to less smoke being evolved.

However, if the ventilation is less than that required for combustion the fire becomes ventilation controlled and the mass burning rate (and hence the vapour evolution rate) decreases to match available air flow. Due to the reduced burning rate, the flame size and heat fluxes to objects from ventilation controlled confined pool fires may be lower than from unconfined fires unless re-radiation from hot compartment walls increases flame temperatures. The restricted airflow may result in an external fire at the vent openings and so areas not previously exposed to fire outside the compartment may now be exposed to flame engulfment and thermal radiation.

In under-ventilated conditions, both the CO and soot levels increase. CO up to 5% v/v may be measured at a vent prior to the onset of external flaming although at the end of an external flame the levels are likely to fall to less than 0.5% v/v. Soot levels up to 3 g m^{-3} might be expected.

3.2.3.4 Confined hydrocarbon pool fires with deluge

When deluge is activated within a confined space, the residence time of the water droplets in the flame and hot walls leads to water evaporation within the flame and a significant reduction in flame temperatures. This then reduces the radiation back to the pool surface and results in a lower mass burning rate. An initially ventilation controlled pool fire may then become fuel controlled at this lower burning rate and any external flaming that had formed is likely to be reduced or to cease entirely.

3.2.3.5 Methanol pool fires

Methanol differs significantly from the hydrocarbon fuels discussed above. It burns with a non-luminous flame that is not visible in normal lighting. No soot is produced and the thermal emissions are dominated by the molecular emissions associated with the production of CO_2 and water vapour. The flame height is about one third that expected from an equivalent sized hydrocarbon pool. The mass burning rate increases with increasing pool size and a value of 0.03 kg m^{-2} s^{-1} has been measured for a 10 m diameter pool. It is not known if the flame has reached ‘optical thickness’ at this scale and hence whether this would increase further for larger fires. The low radiative emissions of the flame results in a low fraction of heat radiated, F, and low heat fluxes to engulfed objects. On an offshore platform, an important hazard may be to personnel entering the flame unwittingly due to its invisibility. In a typical offshore environment, the additional combustion of residual oil, paint and other materials can add some luminosity and visible smoke to the flame.

3.2.3.6 Hydrocarbon pool fires on the sea

Once established, a hydrocarbon pool fire on the sea will behave in a similar manner to an unconfined pool fire on an installation. Consequently, depending on the size of the fire, engulfment of the installation legs and the underside of the platform are possibilities. Flame temperatures of typically 900 to 1200°C can be expected and heat fluxes to engulfed objects up to 250 kW m^{-2}.

Following initial ignition, the flame spread across the surface of a spill on the sea will depend upon the volatility of the fuel, and the wind speed and direction. For oil spills, the rate of flame spread downwind increases with increasing wind speed. The flames tend to spread from the ignition source downwind across the spill without significant crosswind spread and flame spread upwind is slow. The presence of sea currents or regular waves (swell) does not appear to influence flame spread but it may be curtailed by choppy conditions or steep waves.

The significant difference between liquid spills on an installation and liquid spills on the sea is that on the sea it is unlikely that ignition will occur. Overall, the likelihood of ignition is low (especially for less volatile hydrocarbons such as crude oil) due to a number of factors which are discussed below. The likelihood of ignition also decreases with time following a spill, sometimes rapidly, so spills where immediate ignition could occur (or ignition has already occurred) are likely to be the main focus of attention.

Assuming an ignition source is present, there are three main factors that influence the ignitability of liquid spills onto the sea, all of which are time dependent. Their significance in inhibiting ignition increases with time as a result of reducing pool thickness, increasing fuel flash point and emulsification.

Following an initial spillage, the pool will spread out reaching an equilibrium thickness within a few hours, even for a large spillage. This equilibrium thickness depends upon fuel type with typical values of less than 0.1 mm for light crude oils and 0.05-0.5 mm for heavy crude oils. However, there is a minimum pool thickness that is capable of supporting a stable flame; about 0.5 mm for condensate; 1 mm for light crude; and 1-3 mm for heavier oils. When the thickness falls below these levels, the cooling effect of the sea prevents evaporation of the fuel from the pool surface, which is required for combustion. A pool fire will only occur before the equilibrium thickness has been reached. In this case, a steep temperature gradient through the liquid hydrocarbon allows evaporation at the pool surface.

Fuels with a flash point lower than the ambient temperature will ignite readily if the flammable vapour cloud can reach an ignition source. Those with a flashpoint over 100°C (such as stabilised crude oil) will require the presence of a major heat source to achieve ignition, such as a pre-existing fire on the platform. The likelihood of ignition of a liquid spill reduces with time as the lighter fractions evaporate and the flash point increases.

Emulsification of a hydrocarbon fuel with seawater will reduce its flammability significantly. For crude oils, emulsions with over 25% water are considered to be not ignitable. The cut-off point for condensate is unknown, but is likely to be higher. Emulsification of the fuel and water arises primarily as a result of the initial spill conditions and the subsequent weather/sea conditions. Breaking waves and wind speeds over 15 m s^{-1} will promote emulsification and result in low ignitability. The wave action will also cause fluctuations in the pool thickness and may result in breaking up of the pool and thereby prevent sustained burning should ignition occur. Spills that plunge into the sea from the platform (which, if burning, may be extinguished in the process) are likely to break up and begin to emulsify. The least emulsification is likely to occur if spills run down an installation leg or occur close to the sea surface.

In the case of subsea oil pipeline failures in shallow water (<200 m), the oil plume widens as it rises through the water and breaks up into small droplets. Any significant gas component in the oil provides additional initial upward momentum and the oil droplets are likely to break the surface in a location above the original failure and then spread radially. However, the pool may then be carried along by tidal currents and wind. This process provides significant opportunity for emulsification and reduces the ignitability of any resulting pool.

In the case of stabilised crude, the lower initial buoyancy will result in the rising plume being more affected by tidal currents and the oil may reach the surface at a location displaced laterally from the original leak site.

In summary, a low velocity, ignited, large volume spillage of a volatile liquid hydrocarbon close to the sea surface near to the installation in calm or moderate conditions represents the worst case scenario in terms of a pool fire on the sea. Most other scenarios have a low likelihood of producing a pool fire. Experiments have been carried out by SINTEF in two series of experiments at Spitzbergen in 1994 [5].

3.2.4 Gas fires from subsea releases

Loss of containment from a subsea gas pipeline (or a pipeline containing a gas-oil or gas condensate mixture with a high GOR) could give rise to a flammable gas release at the sea surface. For any pipeline failure scenario, the nature of the hazard depends on a number of factors [6]:

- The depth of the water in which the release occurs.
- The mass flow rate of gas from the pipeline.
- The rate at which the plume expands as it rises through the water.
- The degree to which gas is removed from the plume (absorbed by the water or as hydrates).
- The dispersion of the gas released at the sea surface.

In shallow water, the plume of bubbles will increase in radius approximately linearly as it rises through the water approximating a conical plume. When close to the water surface, the streamlines diverge and this may result in the area where the gas bubbles break the surface being twice that expected by conical plume development only.

Whether the resulting gas breaking the surface is flammable will depend on the rate of gas released and the area over which it breaks the surface, which is related to the water depth (as already noted). However, unless the water is very shallow (<10 m), the resulting gas release at the sea surface is likely to be a dispersed low velocity source and burn as a weakly turbulent diffusion flame, strongly affected by the wind. It could be considered as a ‘pool fire’ with an effective mass burning rate given by the release rate divided by the area over which the gas surfaces.

A full bore rupture of a subsea pipeline will result in a highly transient outflow, so the resulting fire hazard will also vary with time. The operation of a subsea emergency shutdown valve (ESDV) may limit the duration of the release and also give rise to a release rate that changes even more rapidly with time.

In deep water (>300 m) formation of gas hydrates is possible and over 500 m some researchers report complete conversion to hydrates, although this also depends on gas composition and water temperature. In such cases, the hydrates will rise solely as a result of buoyancy and are likely to reach the sea surface some distance laterally from the original leak site. Some researchers suggest that water turbulence may keep the hydrates in suspension or that the gas will be absorbed into the water and that, therefore, the gas may never reach the surface. However, the processes involved are complex and more recent publications suggest that more gas may reach the surface than might be expected [7].

An overview of the current understanding of subsea releases has been published by SINTEF [8].

3.2.5 Boiling liquid expanding vapour explosion (BLEVE)

Fire impingement on a vessel containing a pressurised combustible fluid causes the pressure to rise within the vessel and the temperature of the vessel wall to increase. If the inner wall is in contact with liquid, the temperature rise will follow that of the liquid. However, where there is gas on the inside of the wall, the rate of temperature rise will be much greater and the wall can reach temperatures that will significantly reduce its strength.

Even within a short timeframe, this may lead to catastrophic failure and the total loss of inventory. If the liquid is well above its atmospheric pressure boiling point, a flashing process will occur as a rapid phase transition that can generate explosion pressures in addition to those produced by failure of the vessel and expansion of the vapour phase.

These events are known as BLEVEs. This highly transient event generates a pressure wave and fragments of the vessel may produce a missile hazard leading to failure of other items in the vicinity and hence the potential for escalation. In addition, there is a flame engulfment and thermal radiation hazard produced by the fireball.

Onshore, BLEVEs are generally associated with the storage of pressure liquefied fuels such as LPG. Experimental work has shown that a standard LPG storage vessel, incorporating the normal pressure relief valve, can fail catastrophically within 5 minutes of being subjected to a medium sized (<2 kg s^{-1} or ~100 MW) jet fire, despite operation of the relief valve. Following failure, a large approximately spherical fireball is produced which is highly radiative with little smoke obscuration due to the fuel atomisation and vaporisation leading to good mixing with the air. Consequently, the fraction of heat radiated, F, is higher than for a large pool fire involving the same fuel.

The initial upward momentum and vorticity of the fireball causes it to rise into the air as it develops and eventually it burns out when all the fuel is consumed. How much of the initially liquid fuel vaporises and takes part in the fireball depends upon the degree of superheat of the fuel at the time of failure and also whether liquid becomes entrained into the flashing vapour.

In the offshore context, a BLEVE hazard might be considered, for example, in relation to a pressurised separator vessel containing unstabilised condensate and gas. However, a BLEVE is unlikely to develop in the same way as described above for an onshore facility, as the vessel will probably be located within a module amongst other vessels and pipework. The potential for escalation is thus much increased due to the proximity of other vessels and pipework that may be struck by missiles. Additionally, the presence of this other equipment may lead to increased overpressures being developed as the burning gas cloud expands through the congested region. The presence of roof confinement will significantly modify the shape of the developing fireball and lead to increased lateral development.

Even a small inventory of fuel being involved in a BLEVE event (<100 kg) would be expected to produce a fireball extending throughout the entire volume of a typical module. Consequently, apart from the risk of the BLEVE causing escalation, the event presents a severe hazard to exposed personnel. Whilst most personnel would have made their escape from the module before a BLEVE occurs, emergency response and rescue teams could still be exposed to the hazard.

Depending on the type of fire impacting the vessel, pre-activation of deluge (area and dedicated vessel deluge) may prevent or delay the occurrence of a BLEVE. However, the deluge is unlikely to provide any significant benefit in terms of mitigation of the event, especially within the region of potential flame engulfment. The primary defence on most offshore facilities is the blowdown system. This should be designed to reduce pressures to avoid vessel failure before either the fire has been brought under control or most of the inventory has been removed, though PFP applied to vessel walls and supports may also be required to achieve this outcome.

3.3 Estimating fire and smoke loadings

3.3.1 Inventories and release rates

An isolatable section is a section of the process plant that is bounded by ESDVs such that if a release or fire is detected, the closure of the valves will isolate the inventory within that section of the process, preventing any further inflow. The inventories of isolatable sections may vary considerably.

If isolation and blowdown are successful, the maximum duration of the resulting fire will be determined by the time taken to close the ESDVs, the inventory of an isolatable section, and the size of a leak. For inventories that are fully or partially gas, this duration may be reduced by blowdown of the isolated section, though for larger releases this will have a marginal effect as the blowdown rate will be significantly less than the release rate. The main benefit of blowdown is that it reduces the inventories and pressures in other isolatable sections that might be affected by the fire.

The isolation of a leaking isolatable section has the effect that the duration of large gas leaks may be relatively short. For liquid spills, an effective drainage system may limit the inventory involved in a fire. Any fire and explosion analysis should also consider event scenarios where isolation or blowdown fails, or where an isolation failure means adjacent inventories are also available to the release.

The resulting fire size following an accidental release will be strongly dependent on the mass release rate of the fuel, which will be determined by the hole size and pressure. For any particular fire analysis, the mass release rate should be calculated on the basis of the process conditions (composition, pressure, temperature) and the hole size through which the release is occurring.

Release rates are often considered to be constant prior to closure of the ESDVs (that is all of the mass lost is replenished from the process stream and pressures are maintained), but will then reduce once the ESDVs have closed and inventory is lost from the section.

Methods used for the calculation of the mass release rates should be validated for the conditions and fluids being considered. It should be noted that this is particularly important for releases of two-phase fluids, which can be complex to model.

3.3.2 Typical fire parameter values

3.3.2.1 General

Ideally, the fire size and thermal loading from fires should be assessed using mathematical models that have been extensively validated against large-scale data. A range of such models is available on a licence or consultancy basis.

However, it is helpful to provide indicative data for the primary parameters that describe fires. For the six fire types identified and discussed in Section 3.2, tabulated values are provided giving guidance on typical fire sizes and heat loadings for a range of release rates. The values presented were derived from a combination of information in the literature, the results of an extensive body of large-scale experimental data and predictions made by Shell and DNV GL. In essence, the fire loading data presented here is an updated and more comprehensive version of the guidance values published by the

Energy Institute [9]. Information on smoke loading is also based on experimental data gathered by DNV GL and Shell, much of which is not in the public domain.

3.3.2.2 High pressure jet fires – gas and two-phase

Wherever possible, the following information is provided for the release rates, as discussed in Section 3.3.1:

- The expected flame extent, so that items or personnel within that range can be identified and the consequences of flame engulfment considered.
- The fraction of heat radiated, *F*.
- The CO level and soot concentration in the smoke produced.
- The total heat flux to an engulfed object together with the radiative and convective components. Note that these fluxes represent the initial values when the engulfed object is cold. Values of typical flame temperature (T_f), emissivity (ε_f) and convective heat transfer coefficients (*h*) are also provided.
- The effect of deluge in terms of the reduction in the heat flux to engulfed objects and the enhanced attenuation of incident radiation to the surroundings using the effective fraction of heat radiated, *F'*.
- The effect of confinement on fire characteristics and the combined effect of confinement and deluge.

This information is presented in Table 3 for gas jet fires and Table 4 for two-phase jet fires. As discussed in Section 3.2.2.5, for two-phase jet fires the maximum heat fluxes to engulfed objects have been found to occur when the mixture is about 30% gas and 70% liquid by mass. Consequently, the values shown in Table 4 correspond to this worst case condition.

It should be noted in Table 3 and Table 4 that for the largest leaks (i.e. a flow rate >30 kg s^{-1}) a single number is given for the total heat flux which could be interpreted as implying a constant value for all of these larger release rates. Where heat flux calculations are required for larger leak rates, the heat flux figures should be used with caution, CFD simulations can be used to obtain data on the effects of larger fires.

For a high pressure two-phase jet fire involving *x*% liquid (by mass) the fraction of heat radiated, F_m, can be calculated as follows:

$$F_m = \left(\frac{x}{100}\right) \cdot \left(F_L - F_G\right) + F_G$$

where F_G is the fraction of heat radiated for natural gas as given in Table 3 and F_L is the fraction of heat radiated for the liquid fuel involved. Take F_L = 0.24 for C3, 0.32 for C4, 0.45 for C6-C25 (including condensate and diesel) and 0.5 for crude oil.

Table 3: High pressure gas jet fires

Jet Fire Parameter	0.1 kg s^{-1}	1.0 kg s^{-1}	10 kg s^{-1}	>30 kg s^{-1}	Effect of Confinement
Flame length (m)	5	15	40	65	Affected by enclosure shape and openings.
Fraction of heat radiated, *F*	0.05	0.08	0.13	0.13	
CO level (% v/v) and smoke concentration (g m^{-3})	CO < 0.1 Soot ~0.01	CO < 0.1 Soot ~0.01	CO < 0.1 Soot ~0.01	CO < 0.1 Soot ~0.01	Increased CO up to about 5% v/v at a vent prior to external flaming, but after external flaming <0.5% v/v at the end of the flame. Soot levels depend on equivalence ration from about 0.1 g m^{-3} (ϕ=1.3) to 2.5 g m^{-3} (ϕ=2.0).
Total heat flux (kW m^{-2})	180	250	300	350	Increased heat loading up to 400 kW m^{-2}. (280 kW m^{-2} radiative, 120 kW m^{-2} convective, T_f=1600 K, ε_f=0.75, h=0.09)
Radiative flux (kW m^{-2})	80	130	180	230	
Convective flux (kW m^{-2})	100	120	120	120	
Effect of deluge	No effect on heat loadings to engulfed objects. In far field, take F'=0.8F for 1 row of water sprays, F'=0.7F for 2 rows and F'=0.5F for >2 rows at 12 l min^{-1} m^{-2}. May improve combustion efficiency and reduce CO levels within flame.				Risk of extinguishment and explosion hazard if deluge activated when enclosure is already hot and fire is well established.

Table 4: High pressure two-phase jet fires

Jet Fire Parameter	Fuel Mix of 30% Gas, 70% Liquid by Mass				Flashing Liquid Fires (e.g. Propane/ Butane)	Effect of Confinement
	0.1 kg s^{-1}	1.0 kg s^{-1}	10 kg s^{-1}	>30 kg s^{-1}	1.0 kg s^{-1}	
Flame length (m)	5	13	35	60		
Fraction of heat radiated, *F*	See equation above for fraction of heat radiated.					
CO level (% v/v) and smoke concentration (g m^{-3})	CO < 0.1 Soot ~0.01	CO < 0.1 Soot ~0.01	CO < 0.1 Soot ~0.01	CO < 0.1 Soot ~0.01		Increased CO up to about 5% v/v at a vent prior to external flaming, but after external flaming <0.5% v/v at the end of the flame. Soot levels depend on equivalence ratio from about 0.1 g m^{-3} (ϕ=1.3) to 2.5 g m^{-3} (ϕ=2.0).
Total heat flux (kW m^{-2})	200	300	350	400	230	Increased heat fluxes, take values as per 30 kg s^{-1} two-phase jet fire.
Radiative flux (kW m^{-2})	100	180	230	280	160	
Convective flux (kW m^{-2})	100	120	120	120	70	
Effect of deluge	Some benefit to engulfed objects but temperature may still rise although at a slower rate. Combined area and dedicated deluge may prevent temperature rise if effectively applied. See Section 3.2.2.6. In far field take *F′* as per Table 3.					Risk of extinguishment and potential formation of pool.

3.3.2.3 Pool fires on the installation

Two pool fire sizes are considered:

- Small pool (typically less than 5 m diameter)
- Large pool (typically >10 m in diameter)

A small pool fire might typically result for a leak rate in the region of 1 to 2 kg s^{-1} and, within a typical module, it would be expected that sufficient air for combustion would be available. A large pool fire would be expected to produce a flame reaching to the roof of a module. It may also suffer from insufficient air. Consequently, the effects of confinement on fire characteristics as discussed in Section 3.2.3.3 need to be considered.

The following information is provided for pool fires on an installation is similar to that given in Section 3.3.2.2 except that in this case the mass burning rate is provided. This information is presented in Table 5.

3.3.2.4 Pool fires on the sea

For pool fires on the sea, only large spills are considered, as small spills are unlikely to affect the installation. Similarly, only a gas fed fire at the sea surface due to major failure of a 24” diameter subsea pipeline is considered. Table 6 provides relevant fire parameter values for hydrocarbon pool fires on the sea.

The gas outflow from a subsea pipeline will depend on the pressure and the pipeline size. The release will also vary with time, with this variation depending upon the length of pipeline that is depressurising. Similarly, the area at the sea surface over which the gas emerges will depend on the depth and the gas release rate. Furthermore, depending on the gas outflow and the depth, the gas plume at the sea surface may not be within flammable limits. It is, therefore, recommended that appropriate models be used for these processes (e.g. Loes and Fannelop [10]).

For illustrative purposes, predictions of the fire hazard following the rupture of a long 24” diameter natural gas pipeline operating at 100 barg at a depth of 50 m suggest that the fire diameter might be of the order of 100 m with a flame length of 150-200 m. On the basis that the fire is a low velocity laminar flame, it can be regarded as a large pool fire, and the values presented in Table 6 for fraction of heat radiated and heat fluxes are recommended with the mass burning rate set as the average mass release rate at the sea surface.

Table 5: Pool fires on the installation

Pool Fire Parameter	Methanol Pool	Small Hydrocarbon Pool	Large Hydrocarbon Pool	Effect of Confinement
Typical pool diameter (m)	5	<5	>10	Any.
Flame length (m)	Equal to pool diameter	Twice pool diameter	Up to twice pool diameter	See Section 3.3.2.3. Take values as per large hydrocarbon pool fire for worst case. If confinement is severe then mass burning rate will decrease to match available airflow and large external fire at vent expected.
Mass burning rate ($kg\ m^{-2}\ s^{-1}$)	0.03	Crude – 0.045-0.06 Diesel – 0.055 Kerosene – 0.06 Condensate – 0.09 C3/C4s – 0.09	Crude – 0.045-0.06 Diesel – 0.055 Kerosene – 0.06 Condensate – 0.10 C3/C4s – 0.12	
Fraction of heat radiated, F	0.15	0.25	0.15	
CO level (% v/v) and smoke concentration ($g\ m^{-3}$)	Negligible	CO < 0.5 Soot 0.5-2.5	CO < 0.5 Soot 0.5-2.5	Increased CO up to about 5% v/v at a vent prior to external flaming, but about 0.5% v/v at the end of the external flame. Soot levels up to 3 $g\ m^{-3}$.
Total heat flux ($kW\ m^{-2}$)	35	125	250	See Section 3.3.2.3.
Radiative flux ($kW\ m^{-2}$)	35	125	230	Take values as per large hydrocarbon pool fire.
Convective flux ($kW\ m^{-2}$)	0	0	20	
Effect of deluge	Extinguishable using AFFF. Water-soluble but effect of water deluge unknown.	See Section 3.2.3.2. Expect a reduction in flame coverage (and hence flame size) of up to 90% within 10 minutes. Rapid extinguishment with AFFF. Up to 50% reduction in radiative heat flux to engulfed objects.		See Section 3.2.3.4. Expect reduced flame temperatures and reduced or no external flaming. Mass burning rate reduces to match available airflow.

Table 6: Hydrocarbon pool fire on the sea

Pool Fire on Sea Parameter	Value
Typical pool diameter (m)	>10
Flame length (m)	Up to twice diameter
Mass burning rate (kg m^{-2} s^{-1})	Crude – 0.045-0.060 Diesel – 0.055 Kerosene – 0.060 Condensate – 0.100 C3/C4s – 0.200
Fraction of heat radiated, *F*	0.12
CO level (% v/v) and smoke concentration (g m^{-3})	CO < 0.5 Soot 0.5-2.5
Total heat flux (kW m^{-2})	250
Radiative flux (kW m^{-2})	230
Convective flux (kW m^{-2})	20
Convective heat transfer coefficient, *h* (kW m^{-2} K^{-1})	0.02

3.3.2.5 Boiling liquid expanding vapour explosions

BLEVEs are highly transient events in which a fixed inventory is instantaneously released. The subsequent combustion gives rise to a fireball that grows in size to a maximum before burning out as all the fuel is consumed. Consequently, the key parameters of interest in terms of a consequence assessment are the extent of the flame and the incident radiation hazard to personnel outside the flame. These parameters are also highly transient. In relation to incident radiation levels outside the fireball, both the maximum level experienced and the 'dosage' over the duration of the event are of interest in order to determine the effect on people.

3.3.3 Predictive models for fire loading

There are basically three types of predictive models that can be used to predict fire characteristics and the thermal loading from fires, these being:

- Empirical models
- Integral (or phenomenological) models
- Numerical (CFD) models

Empirical models contain, to varying degrees, a physical basis combined with correlations that have been derived from experimental data. They are generally easy to use, but their applicability is limited to the range of experimental data used to derive them. These models may also simplify the source in a way that makes them more inaccurate in the region close to the flame. For example, they may use a point source for the thermal radiation or use a flame length taking no account of the flame shape.

Integral models use equations relating the fire characteristics to the physical processes involved, such as mixing, combustion and thermal emissions. However, the relationships are simplified and are generally 1D. Such models will also often contain some parameters that have been derived from experimental data. Nevertheless, integral models provide an effective method for predicting fire characteristics and are generally easy to use. Strictly speaking, they should only be applied to the range of circumstances for which they have been validated by experimental data. However, because of the physical basis of the equations, the models can be applied, within reason, to situations outside this range.

Numerical models (CFD) attempt to model in 3D the time varying processes within a fire such as the fluid flow and combustion processes. Any CFD model used in analysing fire scenarios should have been validated against large-scale experimental data. However, given the more fundamental modelling approach, the models can in principle be used for complex geometries and conditions significantly removed from experimental data used to validate them.

Fire CFD models should be used by experienced and trained analysts. The greater complexity means that they are not routinely used for general quantitative risk assessments (QRAs). However, they can be useful to study a particular fire scenario in more detail. For example, the impact of potential design changes (such as increased ventilation) can then be evaluated and guidance provided on how to reduce the hazard.

3.4 Heat transfer

3.4.1 Mechanisms for heat transfer

3.4.1.1 General

Basic heat transfer by radiation, convection and conduction is well covered in the standard textbooks (e.g. Incropera and De Witt, 2002 [11]). This section concentrates on determination of heat transfer using the values identified in Table 3 through to Table 6 for key fire parameters. The discussion is largely qualitative with further detail available from FABIG [1].

3.4.1.2 Radiation

Radiation from the hot gases and incandescent soot particles is the main mechanism for transferring heat. For flames with relatively little momentum, e.g. pool fires, radiative transfer to an impinged object represents at least 80% of the heat transferred. Even with impinging high velocity jet fires, radiative heat transfer still represents 50% to 60% of the heat load. For objects outside a fire, all of the heat transfer is through radiation.

The radiative heat emission process to objects outside a fire is modelled by assuming that the radiation comes from the flame surface. The SEP of a flame is the heat radiated outwards per unit surface area of the flame. Generally, a uniform SEP is taken over the whole flame shape but this a gross simplification of what may happen in practice. For example, in a large pool fire, the base of the flame may have the relatively high SEP of 180 kW m^{-2} whereas the smoke obscured flames, which may comprise two thirds of the flame shape, may have the relatively low SEP of 60 kW m^{-2}.

The thermal radiation at any location outside the fire is determined by the view that location has of the flame, the SEP and the degree of attenuation of the thermal radiation by the atmosphere. Atmospheric attenuation is primarily caused by absorption of radiation by carbon dioxide and water vapour and scattering by dust particles and generally has little effect on received thermal radiation over distances of 10 m or less.

3.4.1.3 Convection

Heat transfer by convection occurs when there are hot gases flowing over the surface of the object. Convective heat transfer will always occur to some extent if there is direct flame impingement and, in these circumstances, at least as much radiative heat transfer will accompany it. Convective heat transfer can occur without significant radiative heat transfer if a plume of hot gases is channelled to an object not in direct (or reflected) line of site with the flames, though in general such heat transfer would not be damaging to equipment.

3.4.1.4 Conduction

Heat transfer by conduction is very small compared to the other methods of heat transfer but needs to be taken into account in some circumstances, such as differential heating at the joints between thick and thin thick walled structures. The other conditions where conduction is normally taken into account are where heat is transferred through PFP or through the walls of a vessel or pipe to a fluid inside.

3.4.1.5 Flame geometry

Generally, flames are not static. They will move around in the wind and will vary with the fuel release rate, amount of back radiation etc. For a pool fire, the wind may tilt the flame towards, away from or sideways to the receiver. With jet fires, a co-flowing wind will elongate the flames and a variable crosswind will move the flames from side to side. An understanding of the geometry of the flame is essential in order to apply the heat transfer mechanisms identified in the previous section.

Validated empirical and phenomenological models are available for most of the standard situations but the user needs to be aware of the limitations and simplifications made in the model used if the results are to be relied upon. Summaries and comparisons of these models are available in the standard reference books e.g. ‘Yellow book’ (2005) [12], SFPE Handbook (2016) [13], Lees (2005) [14]. There are also the commercially available suites of programmes, e.g. PHAST by DNV GL and Canary by Quest.

A feature of most of these models is that the SEP used for a particular situation will depend on how the flame geometry is modelled for that situation. Hence, a model using a high SEP and relatively low flame area may/should give the same answer as a model using a relatively low SEP but larger flame area.

In assessing the heat transferred, the key decision is on whether or not the object is impinged by flame. Generally, some conservatism may be applied in defining impingement, such as applying a safety margin to the flame lengths given by a model or the relevant table in Section 3.3.2. Alternatively, the envelope to a particular thermal radiation level, say 150 or even 50 kW m^{-2}, can be used to conservatively define the flame, with everything outside this only receiving radiation.

In practice, the heat transferred to a receiver will depend on whether it is fully, partially or not enveloped in flame and, in partially or totally enclosed modules, how much re-radiation there is from walls, ceilings and process plant.

Whilst detailed analysis may now be made using CFD and finite element analysis (FEA), calculations for an initial analysis can be readily performed if some of the above factors are simplified.

3.4.2 Temperature rise

All the equations given above provide the heat flux to the surface of the receiver. The key requirement is to determine the temperature rise in the item being considered and the time taken to reach the critical temperature for that particular component. The main situations considered are:

- Unprotected steel
- Fire protected steel
- Pressure vessels (unprotected and protected)

As the heat absorbed is a time dependent process, mathematical models, particularly finite difference methods, are used to undertake these calculations. Such models may also simultaneously calculate the heat up of a structure, a vessel or pipe work contents.

Further details on the calculation of temperature rise in unprotected steel and fire protected steel are given in FABIG Technical Note 11 [1]. It should be noted that the temperatures would rise rapidly in unprotected steel engulfed in a jet fire. Critical structural elements and safety equipment will often need some form of protection, often in the form of PFP. Further discussion on PFP is provided in Section 8.7.3, though it is important that PFP performance be verified for the type of fire it is to protect against. Specification and testing of PFP should refer to ISO 22899-1:2007 and ISO/TR 22899-2:2013 [15, 16].

3.4.2.1 Pressure vessels

There are many different processes occurring when a flame interacts with a pressure vessel due to the complex behaviour of the flame, the vessel and the vessel contents. The API has considered the requirements for pressure relief valves (API 520, 2014) [17] and emergency depressurisation systems (ISO 23251:2006, 2005) [18]. However, API only considers relatively small hydrocarbon pool fires and a pressure vessel is much more likely to fail in a jet fire. This was reviewed by Roberts et al. (2000) [19] and the Energy Institute (2003) [9] have published guidance on the effects of severe fires on pressure vessels and SINTEF (2015) [20] have considered this in regard to emergency depressurisation.

The key processes occurring during jet fire impingement on pressure vessels include:

- Heat transfer between the fire and outer surface of the vessel, in the vapour and liquid 'zones', by radiation and convection.
- Heat transfer through the vessel walls by conduction. The wall may comprise of an outer PFP coating plus the underlying steel wall.
- Heat transfer into the vessel fluids by predominantly radiation in the vapour space, and by natural convection or nucleate boiling in the liquid phase.
- Mass transfer out of the vessel through any open or partially open pressure safety valves (PSVs) or the blowdown system.

The processes involved can be complex, involving interacting factors, such as the rate of heat transfer into the vessel fluids and the calculation of their state, which in turn affects the blowdown rate and the internal vessel pressure.

In practice, when a fire impinges on a vessel containing liquid, the wall in contact with vapour will heat up very quickly and the wall in contact with liquid will stay at a relatively low temperature unless film boiling occurs. In propane jet fire trials on unprotected 2 tonne LPG tanks (Roberts et al., 2000) [19] the vapour wall reached up to 870°C on failure whilst the wall in contact with liquid did not exceed 230°C. Failure of a vessel engulfed in a jet fire can occur within a few minutes if unprotected.

The objective of protective systems is to prevent temperature rise (fire protection) or to reduce the pressure faster than the rising temperature is weakening the vessel wall (blowdown). These systems need to be effective long enough for either the fire to be brought under control or the majority of the contents to be removed before failure [15, 16, 17].

Models are available that take these factors into account. Persaud et al. (2001) [21] have applied the Shell HEATUP model to the heat up and failure of LPG tanks. The Petrell VessFire model also allows analysis of vessel response under different fire protection and blowdown scenarios. The models take into account the physics describing heat and mass transfer processes, the fluid properties and determine the potential for vessel failure by comparing the hoop stress with the ultimate tensile strength of steel as the vessel wall temperature rises.

3.4.2.2 Effect of fire protection on heat transfer to vessels

Directed water deluge

No credit is given for directed deluge systems in ISO 23251:2006 [18] as the reliability of water application is uncertain because of freezing weather, high winds, clogged systems, unreliable water supply and vessel surface conditions that can prevent uniform water coverage. However, it is suggested that systems designed to NFPA 15 [22] can be effective. NFPA specifies an application rate of 12 l m^{-2} min^{-1}. This is derived from small-scale pool fire trials where the application rate is taken as the amount of water leaving the nozzles divided by the vessel surface area. The NFPA requirements for nozzle spacing and spray angle are very general. In practice, it is the amount of water flowing over the surface of the vessel, which has the greatest influence on fire resistance. As only between 35% and 45% of the water leaving the nozzles actually forms a film on the vessel surface, a poorly designed system delivering the minimum requirement of 12 l m^{-2} min^{-1} may not even fully protect against a pool fire. Although the application requirement of 10 l m^{-2} min^{-1} in the FOC tentative rules (1979) [23] is lower than the NFPA requirement, systems designed to the latter standard will, in general, apply more water to the surface of the vessel as there is a more detailed specification of the nozzle spacing (longitudinal and stand off from the surface), numbers of rows of nozzles and spray angle relative to the size of vessel.

Shirvill and White (1992) [24] have shown that deluge systems with the usual medium velocity nozzles are not effective in protecting against natural gas jet fires. Lev (1995) [25] has suggested that it may be possible with systems using high velocity nozzles and Shirvill and White suggest it may be possible with high velocity water monitors. Shirvill (2004) [26] has shown that a system delivering about 17 l m^{-2} min^{-1} is not effective in fully protecting vessels (keeping the wall temperature to 100°C or less) against 2 to 10 kg s^{-1} flashing liquid propane and butane jet fires. Roberts et al. have shown that about 30 l m^{-2} min^{-1} will protect 2 tonne vessels against 2 kg s^{-1} flashing liquid propane jet fires. Hankinson and Lowesmith (2003) [27] have looked at the effectiveness of area and directed deluge in protecting against 'live' jet fires. Even though a directed deluge system may not be fully effective (primarily in protecting the unwetted wall) in protecting against flashing liquid propane and butane jet fires, Shirvill [26] suggested that the overall rate of heat transfer is reduced by 50%. This is consistent with results (Roberts, 2003) [28, 29, 30] from 20% filled LPG tanks.

Passive fire protection

PFP materials are suitable for protecting LPG tanks against hydrocarbon pool fires.

In general, PFP materials that have successfully passed a test illustrating resistance to jet fire by meeting the required time to critical temperature (ISO 22899-1:2007, ISO/TR 22899-2:2013) [15, 16] will be suitable for protecting pressure vessels against jet fires. Selection of any PFP should be based on the fire scenarios anticipated, in terms of both the type of fire and its duration. Factors such as the time to complete evacuation may also play a part in the specification of any protection.

3.4.2.3 People

The response of personnel to thermal effects is not just dependent on the level of thermal radiation to which they are exposed but also to the duration of this exposure. However, some guidance is framed in the context of the magnitude of received radiation. For example, API [17] provides permissible design thermal radiation levels for personnel. These are given in Table 7 below (note ISO 23251:2006 [18] should be consulted to consider these in the context in which they are given).

Table 7: API/ISO 23251:2006 permissible radiation design levels

Permissible Design Level ($kW\ m^{-2}$)	Conditions
9.46	Maximum radiant heat intensity at any location where urgent emergency action by personnel is required. When personnel enter or work in an area with the potential for radiant heat intensity greater than 6.31 $kW\ m^{-2}$, then radiation shielding and/or special protective apparel (e.g. a fire approach suit) should be considered[a].
6.31	Maximum radiant heat intensity in areas where emergency actions lasting up to 30 s may be required by personnel without shielding but with appropriate clothing[b].
4.73	Maximum radiant heat intensity in areas where emergency actions lasting 2 to 3 minutes may be required by personnel without shielding but with appropriate clothing[b].
1.58	Maximum radiant heat intensity at any location where personnel with appropriate clothing[b] may be continuously exposed.

Notes:

a. *It is important to recognise that personnel with appropriate clothing cannot tolerate thermal radiation at 6.31* $kW\ m^{-2}$ *for more than a few seconds.*

b. *Appropriate clothing consists of hardhat, long-sleeved shirts with cuffs buttoned, work gloves, long-legged pants and work shoes. Appropriate clothing minimises direct skin exposure to thermal radiation.*

More generally, the lethality to the population is usually addressed by probit analysis, which is based on the dose of thermal radiation received over time. More details on using these and other methods are available in publications such as those from the HSE [31] and Lees et al. (2005) [14]. These publications also provide links to many other relevant documents.

4 Derivation of explosion loads

If a release is not ignited immediately, there is the potential for a flammable gas cloud to form. Ignition of this flammable cloud can, in certain conditions, lead to an explosion that generates damaging pressures.

The consequences of an explosion will be affected by the composition and size of the gas cloud, the degree of congestion and confinement in the region into which the release occurs and the location of the ignition source. In its most detailed form, therefore, a calculation of the consequences of a particular explosion scenario would involve:

1. Calculation of the time history of the release rate from the process system being considered. This can take account of the activation of the emergency shutdown (ESD) and blowdown systems that have the effect of limiting the amount of gas released.
2. Prediction of how the gas or vapour cloud develops and disperses under specified wind and ventilation conditions. This will provide an estimate of the volume and extent of the cloud within the lower and upper flammable limits (LFL and UFL). This estimate may be in a time dependant form.
3. Simulation of the explosion for specified conditions in terms of ignition location and gas cloud. This would generally use a homogeneous stoichiometric representation of the gas cloud rather than the actual cloud shape and concentration range determined from the dispersion analysis.

This section describes the important physical mechanisms and factors involved in dispersion and pressure generation, and reviews the types of models that can be used to calculate both gas dispersion and explosion loads. As with fire models, the complexity of the modelling approaches varies from correlations through to CFD.

This section does not address how the models are used to define design loads for structures, which is often risk based involving the analysis of many explosion scenarios. This aspect is discussed separately in Section 5.

4.1 Overview of mechanisms and important factors

4.1.1 Dispersion

Dispersion is a term generally used to refer to the spread and build-up of flammable concentrations as a result of a release of hydrocarbons from a process stream. The main factors that can affect dispersion include:

- The physical arrangement of the area in which the release occurs, particularly the size, degree of confinement and the level of process congestion.
- The composition of the fluid being released and the release characteristics (e.g. hole size, fluid pressure, inventory available for release), often described as the ‘source conditions’.
- The release location and its orientation.
- For naturally ventilated areas, the wind speed and direction. For confined areas with mechanical ventilation, the air change rate and the ventilation pattern.

The physical arrangement can affect the ventilation rate for any given wind speed and direction for any area not mechanically ventilated. Obstructions can also influence the release and the way it mixes with air. Confined, mechanically ventilated areas will generally have lower air change rates compared to naturally ventilated areas. As a consequence, flammable clouds can be generated by smaller releases.

The source conditions are affected by the fluid composition and the outflow from the process system. The outflow has already been discussed in Section 5. However, in the case of a dispersion analysis the proportion of the fluid released that forms vapour is important. For gas releases (and some two-phase releases), all of the fluid will be in the vapour/gas phase.

For releases that involve a mix of lighter and heavier hydrocarbons, some of the released fluid may 'dropout' as liquid, which will not contribute to the dispersion of flammable vapour/gas to any significant degree.

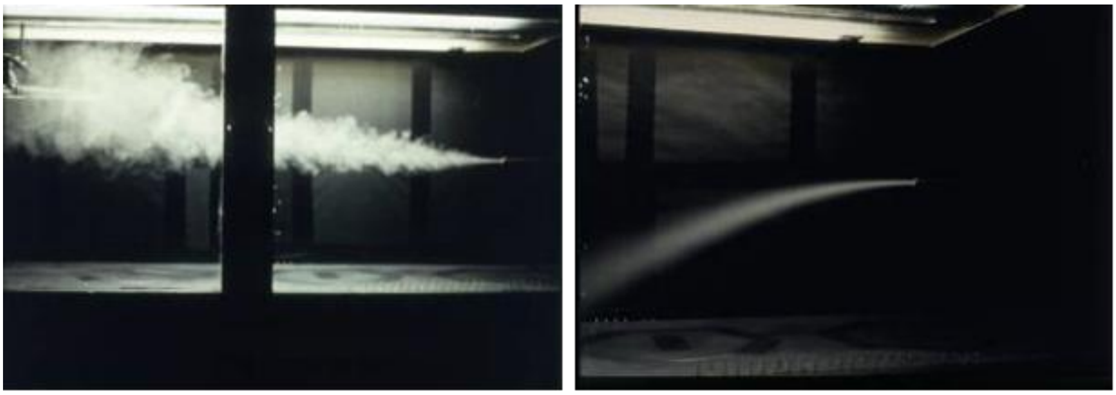
In the case of higher pressure releases, the vapour/gas will be released as a jet. If the jet is free and unimpeded, air is entrained into the jet until the mixture becomes flammable. There will always be a flammable region in the jet, but this may not extend outside the jet envelope and could, therefore, be relatively small. However, if the jet hits obstructions and loses momentum or is directed against the wind and stalls, there is the potential for mixture to be spread more widely and to be re-entrained into the jet. In these circumstances, a more widespread flammable cloud may be produced in the bulk volume of the atmosphere. This is more likely to occur in a module that is mostly or completely confined.

Flammable clouds may also be produced by liquid releases where there is no immediate flashing of vapour but the flash point of the liquid is below ambient conditions. Vapour production rates are likely to be lower in these circumstances and less likely to produce a significant flammable cloud unless there is poor ventilation. The vapour production rate is likely to be enhanced if the liquid spill falls some distance to the deck. Break-up of the liquid flow into droplets as a result of falling from height, for example, can enhance vapour production [1].

It is also possible for a liquid stream released under pressure to produce a flammable mist-air cloud. In these cases, the liquid droplets are formed by mechanical break-up of the liquid stream and if small enough (typically with diameters of less than 100 microns) will have combustion characteristics similar to a flammable gas-air mixture. This may be combined with vapour production as well. Assessment of such mixtures is complex and there is limited experimental data.

The fluid composition can also affect the dispersion behaviour as a result of the density of the vapours. Figure 9 shows the dispersion of two jets, one lighter and the other heavier than air. It is clear that the location of any flammable cloud can be significantly affected by the density of the vapour or gas (the term often used is 'buoyancy', which can be positive or negative depending on whether the vapours are lighter or heavier than air).

Figure 9: Lighter (left) and heavier (right) than air jet releases



Source: Picture courtesy of DNV GL Spadeadam Testing & Research

It is also worth noting that the right-hand picture in Figure 9 has been taken with a long exposure, smearing out the turbulent eddies shown in the shorter exposure time picture on the left. The turbulent eddies are features that would not generally be captured in dispersion modelling.

There have been a number of dispersion studies in open environments but fewer in geometries representative of offshore facilities. However, one particularly relevant study involved a program of 66 full-scale experiments at DNV GL Spadeadam Testing and Research in a test rig representative of an offshore module [2].

As with a fire analysis, a dispersion analysis might be carried out for a defined and constant mass release rate, or it may use a transient mass release rate, taking account of the properties of the process system. Again, the inventory in the process system and the time taken to isolate it will be important in a transient analysis.

Factors that can influence dispersion, in addition to the source conditions, include:

- Ventilation arrangements.
- Location of large rooms and equipment.
- The configuration of walls and type of decks (solid or grated).

These factors can be optimised in design to improve natural ventilation. In addition, a platform can be aligned to maximise the use of the prevailing wind direction, though as any wind direction and speed is potentially possible, this is a risk reduction measure rather than one that guarantees high ventilation rates. The process of optimising natural ventilation does need to take account of working conditions where the external weather conditions can be severe.

For more confined volumes, ventilation will be significantly reduced and where confinement is at or near 100%, will require forced ventilation. This would generally be 12 air changes per hour; however, it should be noted that this is significantly less than the natural ventilation in a more open module. Consequently, a flammable cloud can form with lower release rates compared to an open module.

4.1.2 Gas explosions

4.1.2.1 Pressure generation

Gas explosions can be defined as the combustion of a premixed gas (or vapour) cloud containing fuel and an oxidiser that can result in a rapid rise in pressure. Gas explosions can occur in enclosed volumes such as industrial process equipment or pipes and in more open areas such as naturally ventilated offshore modules or onshore process areas.

Ignition of a flammable gas cloud can result in damaging overpressures if the cloud is within confinement and/or contains congestion in the form of, for example, process pipework. The overpressure caused by the explosion will depend, amongst other things, on:

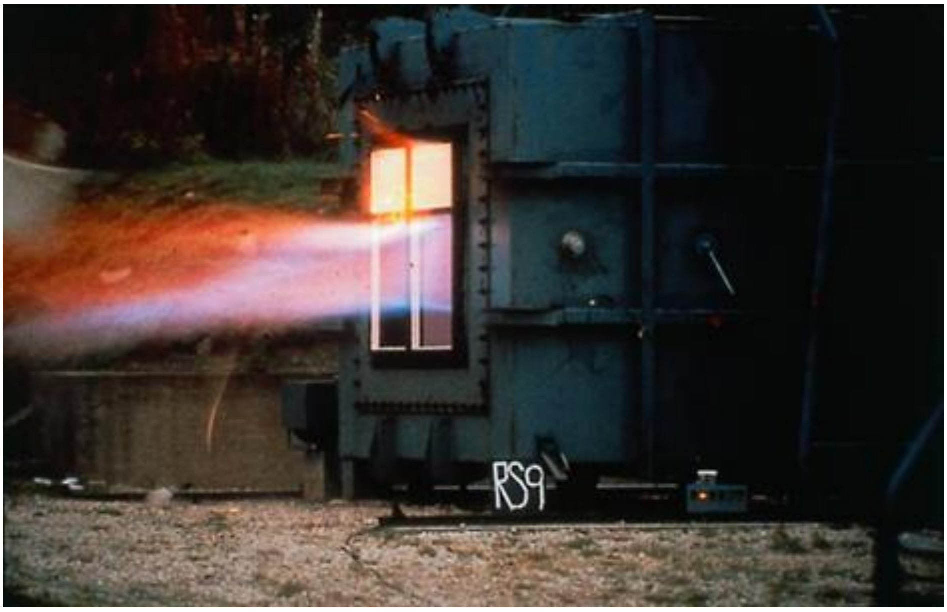
- The type of gas or gas mixture present
- The cloud volume and concentration
- The ignition source type and location
- The degree of confinement surrounding the gas cloud
- The characteristics of any congestion or obstacles within the original cloud and the surrounding area (size, shape, number, location). The congestion outside the original cloud can be important, as there will be some expansion of the cloud during the combustion process.

Combustion of a flammable hydrocarbon-air cloud generates hot combustion products that, due to their higher temperature, would normally expand to occupy a larger volume. If the cloud is in a confined volume, the hot combustion products cannot expand and the pressure within the volume rises. This is generally known as a confined explosion and given the typical flame temperatures the maximum overpressure that can be generated is about 7 barg. Structures will generally fail long before this pressure is reached, effectively limiting the maximum overpressure, as once failure occurs, the hot combustion products can vent from the structure. However, if the rate of generation of combustion products within the confined volume is greater than the ability of the vents to release this volume, then the overpressure will continue to rise.

In addition, once failure occurs and venting starts, some unburnt mixture can be expelled from the confinement before the flame emerges. This unburnt mixture will be turbulent and when the flame burns into it, an ‘external explosion’ can occur. This can, in turn, affect the continuing combustion within the chamber, giving an additional pressure peak.

A picture of a confined explosion showing the venting of the hot combustion products is given in Figure 10. In this case, the venting is through a glass window and it is notable that the flame does not extend all of the way down the window, with the lower part being air. This is because the explosion involved a natural gas air mixture, which is less dense than air. As discussed in the previous section, buoyancy can affect where a flammable cloud develops and in this case a ‘high level’ flammable layer of natural gas and air has developed above the release point.

Figure 10: Confined explosion showing venting combustion products



Source: Picture courtesy of DNV GL Spadeadam Testing & Research

Confinement does not explain all types of hydrocarbon-air explosions. There have been a number of major explosions involving large releases of hydrocarbons where the flammable cloud was not confined. These events are often known as VCEs; examples of major onshore VCEs in the UK are Flixborough, 1974 [3], and Buncefield, 2005 [4].

In VCEs, pressure is generated by accelerating the flame to high speeds, typically over 200 m s^{-1} (for comparison the ambient speed of sound is about 340 m s^{-1}). The flame generates pressure because of the inertia of the unburnt gases in front of the flame resisting the forward movement of the flame.

The cause of the flame acceleration lies with the interaction with repeated obstacles, such as process congestion, within the flammable cloud. If the gas cloud is unconfined, the products behind the flame front are free to expand and will generate an outward flow ahead of the flame. The speed of this flow will be small initially but as the flame front encounters obstacles and follows the flow around them, the flame will distort, increasing its area and the rate at which combustion products are generated. This will increase the flow speeds ahead of the flame, eventually leading to the generation of turbulence in the wake of obstacles, which in turn increases the rate of combustion further.

This can result in a positive feedback mechanism producing successively higher flame speeds and increasing overpressures as the flame progresses through process congestion. It is worth noting that partial confinement of process congestion can increase flame acceleration significantly. If the confinement restricts flow out of the congested area, it will increase the flow through congestion as the flame moves to open vents. This will increase the generation of turbulence and the flame speed.

In this mode of combustion, the VCE can be described as a deflagration, where flame speeds can range from say 100 m s^{-1}, generating about 100 mbar overpressure, to speeds in excess of the ambient speed of sound, where overpressures may reach values of several bar. An important aspect of deflagrations is that the high flame speeds are dependent on the continued presence of obstacles. Once the flame passes into an open area (no obstacles or confinement), it rapidly decelerates and pressure generation stops.

Experimental studies of deflagrations have previously been carried out to provide data for model development, often using idealised regular obstacle arrangements as shown in Figure 11.

Figure 11: Deflagration experiment using idealised obstacle grid

Source: Picture courtesy of DNV GL Spadeadam Testing & Research

However, there is the potential to generate another mode of flame propagation known as a detonation. This involves a shock wave that compresses the flammable mixture to a state where it is beyond its autoignition temperature. The shock wave and combustion zone are coupled and the detonation will typically propagate at 1500-2000 m s^{-1} and result in short duration overpressures of 15-20 barg. Unlike a deflagration, a detonation is self-sustaining and is not dependent on the presence of obstacles. It will continue to propagate through the gas cloud as long as the fuel concentration is within the detonable limits, which are often similar to the limits of flammability.

It had been considered that major VCEs with hydrocarbons had mostly involved deflagration only. However, research into the Buncefield explosion [5, 6] showed that the evidence could only be explained by known mechanisms if DDT had occurred relatively early following ignition of the cloud. Assessment of other onshore VCEs also suggests that DDT may be much more frequent in VCEs than had previously been considered [7].

The transition to detonation generally occurs as the deflagration exceeds the ambient speed of sound, when shock waves begin to form in front of the flame. The shock waves reflect off obstacles back into the flame, enhancing combustion to a degree that can lead to DDT.

This conclusion regarding major VCEs is dependent on the type of fuel released. Methane has a much lower propensity to undergo DDT than fuels such as ethane [8], propane, butane and other higher hydrocarbons. Large-scale experiments with natural gas-air mixtures [9] have generated high flame speeds, well in excess of the ambient speed of sound, without DDT occurring, though for one full-scale test, it has been suggested a detonation occurred in a small part of the gas cloud [10].

The general implications of this understanding for the potential for explosions in offshore oil and gas structures are:

- The combination of partial confinement with process congestion that often occurs in offshore facilities means that there is the potential for severe explosions.
- Explosions following the release of fuels with high methane content will be highly unlikely to undergo DDT, though flame speeds in excess of the ambient speed of sound, with overpressures of several bar are still possible.
- Explosions following the release of fuels comprising mostly higher hydrocarbons and low in methane content may undergo DDT. However, the practical significance of this is likely to be low as:
  - It is unlikely that the structure would be designed to withstand the pressures required to initiate DDT, so the consequence of exceeding these further may be minimal.
  - Unlike onshore sites, there is much less potential for the flammable cloud to extend beyond the process congestion, thus the region where pressure are generated will not change to any real degree.

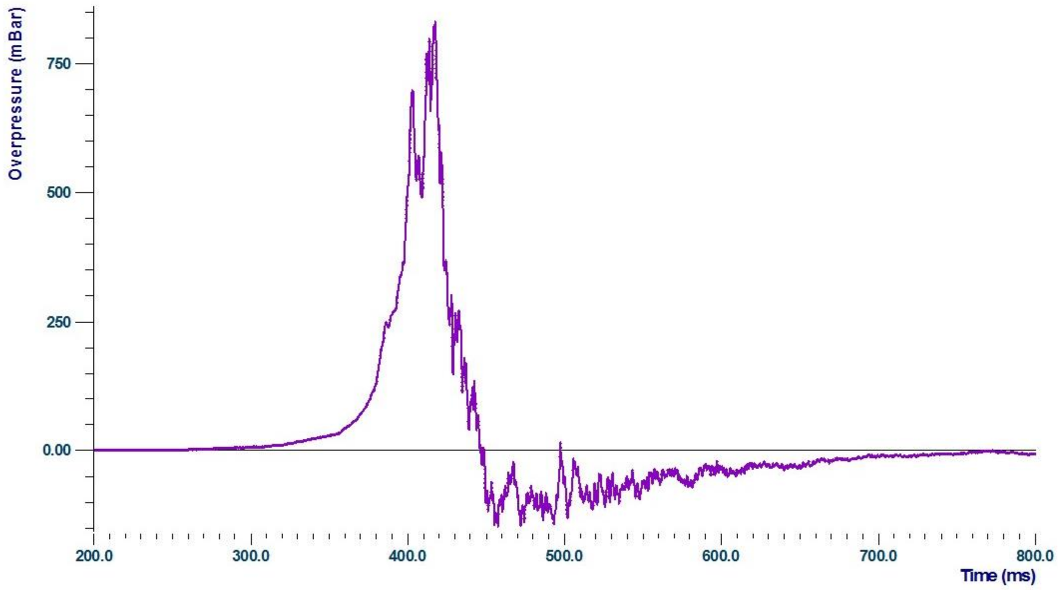
Though there are a number of experimental studies relevant to explosions in offshore facilities [11], the benchmark data for model validation was provided from full scale offshore geometry experiments carried out by DNV GL Spadeadam Testing and Research [12, 13, 14] in the period 1995 to 1999. Figure 12 shows an experiment in this test facility.

Figure 12: Full scale offshore geometry experiment

Source: Picture courtesy of DNV GL Spadeadam Testing & Research

Figure 13 shows a representative pressure/time profile from the full-scale experiments. The maximum pressures varied from test to test, but overpressures of several bar were measured in some of the tests. The duration of the internal pressure loading was typically in the range of 50-100 ms.

Figure 13: Representative pressure/time profile from full scale test



For both confined explosions and VCEs, the expansion generated by the combustion in any congested region can result in turbulent unburnt mixture being driven out of the explosion volume. When the flame burns into this mixture, it can continue to accelerate for a short distance outside the explosion region, generating what is often described as an external explosion [15].

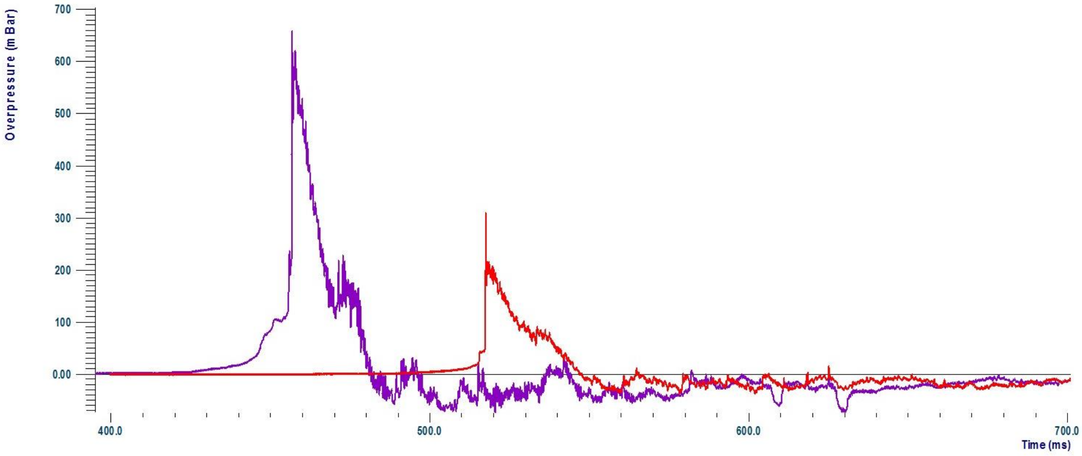
The externally generated pressures, combined with the pressures generated within the explosion source, give rise to a blast wave that will propagate into the surrounding atmosphere and may impinge on neighbouring structures, particularly the TR.

Pressure disturbances at the back of the external blast wave will tend to catch up with those at the leading edge of the pulse. This has the effect of decreasing the rise time in the positive part of the pulse and a 'shock wave' with essentially zero rise time can develop. The peak pressure will also decrease with distance.

An example of this process is shown in Figure 14, which shows two pressure time profiles measured at two locations outside one of the full scale tests described above. The profiles show the variation of pressure with time, with the second profile being measured at a location further from the test rig than the first. It can be seen that the shock wave in the second profile has absorbed more of the pressure disturbances and that the magnitude of the pressure has reduced.

The figure also shows that a 'negative phase' follows the positive overpressure. In this negative phase, the pressure perturbation below ambient is to a much smaller magnitude than the pressure in the positive phase, but with a significantly longer duration. As a result, the net impulse will be reduced and can be close to zero. Simple methods exist for calculating the form of this blast wave and its effects on targets in its path [16, 17]. Some are taken from military and nuclear codes.

Figure 14: Propagation of external pressure wave in full scale explosion test



The blast wave will be affected by other objects, such as decks, blast walls and accommodation blocks, resulting in reflection and diffraction of the blast wave. It is important to note that a wall does not necessarily fully protect items on the opposite side to the explosion, as the blast wave will diffract around the wall. The presence of the wall will, however, reduce the pressure loading for items relatively close to the wall. The further away the item is from the wall, the less this benefit will be.

4.1.2.2 Received loading

Received loading is the loading actually experienced by an item located within or nearby an explosion. Loading can be generated by the pressure field generated by the explosion or the high speed flows associated with the explosion.

In the area of the explosion, large components of the structure such as solid decks or walls experience loads due to the pressure differences on opposite sides of the structure. There can be a strong variation of the spatial and temporal pressure distribution, so the peak pressure on a wall, for instance, may not be applied at all locations at the same time.

For smaller objects such as piping, the pressure applied to the front and reverse side of such items will be of approximately the same magnitude at any moment in time and, in this case, the overpressure field will not apply any net load to the object. For this type of object the dynamic pressure associated with the gas flow in the explosion, generally termed drag loading, will dominate the applied loads. The loads will likely be greatest near open boundaries of the geometry where the explosion occurs, as the flame speeds (and, therefore, the flow speeds) will normally be at a maximum in these areas [18].

Loads acting on intermediate sized objects such as large vessels can be a combination of pressure differential and drag load depending on where the vessel is located and the nature of the explosion.

Where a blast wave propagating from an explosion hits a surface that is not parallel with the direction of propagation of the wave, the received loading will be greater than that in the incident blast wave. This is particularly relevant to structures outside the area in which the explosion is taking place being hit by a propagating blast wave. At the pressure levels typical of a blast wave generated by a hydrocarbon explosion, this received pressure can be up to twice the incident pressure for surfaces orthogonal to the direction of travel.

4.1.2.3 Effect of water deluge

Experimental studies carried out by DNV GL and Gexcon have shown that activation of water spray systems before ignition of a gas cloud can significantly reduce the pressures that would otherwise have been produced.

DNV GL conducted tests in two reduced scale geometries representative of offshore modules (up to about 180 m^3 in volume) and in all cases, the presence of general area deluge at the time of ignition led to a reduction in the explosion overpressures, particularly in cases involving the highest overpressure without deluge.

A more in-depth experimental study by DNV GL was carried out to investigate the performance of water sprays under different explosion conditions [19]. The study involved characterisation of two water spray nozzles types, including measurement of the droplet size distribution. The explosion tests were carried out in a 180 m^3 explosion chamber.

The advantage of using the explosion chamber was that it could be configured with one face completely open, where in high flame speeds were needed to generate significant overpressures and also with only a small vent, resulting in pressure generation by confinement rather than high flame speeds.

The experiments showed that for the case with the open vent and high flame speeds, the pressures were reduced significantly, with experiments generating 3 bar in the absence of water sprays producing pressures of about 0.75 bar with water sprays. For the small vent case, however, the pressures increased slightly.

At the same time Gexcon were also carrying out studies that gave consistent results [20, 21].

Modelling showed that there is insufficient surface area in the water droplets from a standard water deluge system to extract a significant amount of energy from the explosion flame. Droplet sizes are typically 700-800 microns in diameter, whereas the calculations suggested droplets of 10-20 microns were required. The explanation of the experimental results is that the high flow speeds ahead of the flame give droplet break-up in the open vent tests, resulting in explosion mitigation. In the small vent tests, however, no droplet break up occurred in the chamber as the flow speeds were too low, and the turbulence generated by the sprays resulted in a small increase in pressures.

Water sprays tests were also conducted as part of the full-scale tests carried out at DNV GL Spadeadam Testing and Research [12, 13]. The overpressures were reduced in all of the general area deluge experiments in comparison with equivalent tests without water sprays. In addition, the use of water spray curtains also reduced the overpressures, though not by as much as the general area deluge.

The full-scale experiments indicate that in many configurations found in offshore process topsides, activation of water spray systems would reduce the explosion overpressures. Such a change can be attractive in that the systems may already be present for fire protection; however, it is important that electrical equipment be maintained correctly such that it prevents water ingress.

4.1.3 Mist explosions

The pressurised release of hydrocarbon liquids can form a flammable cloud of aerosol or mist which, when ignited, can result in an explosion, as discussed in an information note prepared by the HSE [22]. The mist could be caused by either mechanical break-up of the liquid stream or condensation of a hot hydrocarbon vapour release into a cooler environment.

Droplets of diameters in the range of 20 µm to 40 µm are prime concern as ignition energies tend to be at a minimum at this diameter range and they can stay airborne for a longer duration than larger droplets.

A flammable mist presents an explosion hazard similar to that of a flammable gas cloud in that its volume needs to be sufficiently large to cause damaging loads (overpressure and drag) and be capable of being ignited. Higher hydrocarbons, such as diesel, have lower autoignition temperature than methane (~230°C cf. 580°C). This means potential ignition for flammable mists can include hot surfaces that would not be able to ignite a gas cloud that is predominantly methane.

There has been limited experimental study of mist explosions. Because of the difficulty in characterising the initial conditions, their study is experimentally challenging. The liquid droplets are likely to be accompanied by a vapour, which may in itself be flammable if the flash point of the liquid is less than ambient temperature.

Mist from flammable liquid is known to have a wider flammability range than the equivalent substance in gaseous state. Very fine droplets (~< 10 µm) would have flammability range similar to that of vapour. As diameter increases, the concentration at the LFL reduces. Unfortunately, the data on this is sparse.

There is a significant amount of data on the burning velocity of common hydrocarbon-air mixtures and the effect of fuel concentration. Such data is a fundamental part of any modelling of gas explosions. Comparable data does not exist for mist explosions, primarily due to the complexities of defining the mixture characteristics. The limited guidance available recommends using propane as a representative fuel in explosion models. However, there is no real guidance on how the effect of stoichiometry can be taken into account. A cautious approach may be to use stoichiometric propane-air in all cases.

4.2 Dispersion analysis

There are various methods available for assessing the dispersion of flammable vapour/gas, from correlations to CFD.

Two examples of simple approaches are given here, being the workbook approach developed in the JIP on ‘Gas build up from high pressure natural gas releases in naturally ventilated offshore modules’ [23], and the simplified method given in the ‘Explosion Handbook’ [24]. Though not discussed in detail here, other modelling approaches have been developed using a simplification of the physical mechanisms. This includes the Shell DICE Random Walk model and the DNV GL DISRUN zonal model, both of which have been compared with large and full-scale experimental data. Both models are essentially proprietary but both provided reasonable predictions of the gas build-up and dispersion in the experiments [14].

It should be noted that a ventilation study might be carried out as a precursor to a dispersion analysis or in some cases on its own. The ventilation analysis can be used to identify 'dead' zones where ventilation is poor. The dispersion analysis may then examine the consequences of a gas release near these zones to determine if the ventilation needs to be improved. The CFD models used for dispersion can generally be employed to carry out a ventilation study; however, where an existing installation is being considered, it is also possible to carry out a ventilation survey to support the modelling.

4.2.1 Simple modelling

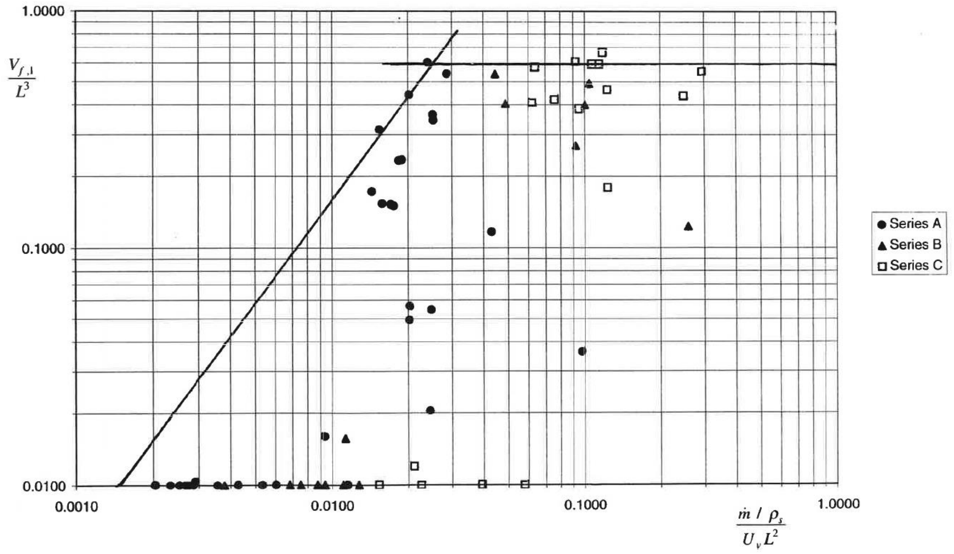
4.2.1.1 Workbook approach for calculation of gas cloud size

Cleaver [25] describes an investigation of gas build-up in naturally ventilated offshore modules following high pressure releases. This work was based on an experimental program of 66 experiments in a full-scale test rig at DNV GL Spadeadam Testing and Research. The objective of the experiments was to investigate the effects on the dispersion process of release location, orientation, pressure and diameter as well as module perimeter confinement and the wind driven ventilation rate.

The experiments were carried out in three series (A to C) with different confinement conditions. The majority of the releases were at a constant rate of between 0.5 to 10 kg s^{-1} but the effects of declining release rates were also considered. Gas concentration during the gas release event was recorded at up to 200 locations within the rig.

The data was used to provide plots of the upper bound estimate of the fraction of the module filled with flammable gas (between 5 and 15% concentration) against the non-dimensional parameter, *R*, as illustrated in Figure 15.

Figure 15: Non-dimensional flammable volume versus release parameter [23]



The release parameter, R, is defined as:

$R = (\mathrm{d}m/\mathrm{d}t) / (\rho_s U_V L^2)$

where

$\mathrm{d}m/\mathrm{d}t$ is the mass flow rate of gas released into module (kg s^{-1})

ρ_s is the density of the released gas is the mass rate of air entrained

U_V is the average ventilation velocity in the module before the gas is released (m s^{-1})

L is the cube root of the module volume

It was generally found that greater confinement gave lower ventilation rates and larger flammable cloud volumes; however, it should be noted that the larger releases themselves changed the ventilation flow within the test rig.

In reference [23], this approach is extended to a ‘workbook’ form. This requires the separate determination of the ventilation flow rate through a confined and congested region and the determination of the flammable gas cloud volume. Two estimates of the flammable volume are made:

- An upper but realistic estimate of the flammable volume that a given release would produce for use at the ‘screening’ stage. In this case, the term ‘realistic’ means it is possible in practice, but will be worst case.
- A mid-range estimate of a typical flammable volume that a release will produce to give a ‘best estimate’ of the likely outcome. There will be situations where larger cloud volumes can be produced.

The flow through the module is characterised by a representative ventilation velocity that is assumed to be related to the external wind velocity. Four generic module layouts are referred to specific details are not described. The normalised volume of the flammable gas cloud is also defined by a non-dimensional relationship. Finally, a relationship for flammable gas volume between two given concentrations is given.

This methodology can provide estimates of the flammable cloud volume that are cautious for the range of situations encompassed by the experimental studies. In reality, many scenarios will give smaller cloud volumes than estimated by the ‘upper bound’ correlation.

4.2.1.2 Explosion handbook approach

A further simple method of calculating gas accumulation in a module is described in the 'Explosion Handbook' by Czujko [24]:

$$M_g = \frac{L_{Vent}}{L_{Module}} \frac{R_{Leak}}{R_{Ventilation}} 3600$$

where

M_g is the mass of gas in the process area (kg)

L_{Vent} is the distance to module vent or end of congested area (m)

L_{Module} is the length of module (m)

R_{Leak} is the gas leak rate (kg s^{-1})

$R_{Ventilation}$ is the Ventilation rate (air changes per hour)

The distance L_{Vent} should take account of the direction of the release. For example in the case of a release point on the edge of a module pointing inwards, $L_{Vent} = L_{Module}$ and not zero. The model essentially assumes perfect mixing in the zone downstream of the release point. It is stated that this simple model will often give a reasonable estimate of the amount of gas within the module, provided that the ventilation flow field is close to uniform. For more complex flow fields the model uncertainty increases.

It should be noted that though the method may provide a reasonable estimate of the mass of gas in the cloud, it does not provide a conservative means of calculating the flammable volume. If the mass were evenly distributed through the full volume of the module, then it may be below the LFL everywhere and, therefore, suggest there is no flammable cloud. However, if the cloud had an uneven concentration, as is likely, then a portion of the cloud may be flammable.

The model also does not adequately represent the differences between cases where the release is more jet like compared to ones where there is some mixture recirculation.

4.2.2 Computational fluid dynamics modelling

The use of CFD has the advantage that ignition sources and their position in the gas cloud may be modelled with the effect of wind speed and direction being represented explicitly. In addition, as discussed earlier, it can also be used to carry out detailed ventilation modelling. The use of CFD in ventilation modelling has the benefit that the results can be used directly to aid the design process.

The software used for the ventilation and dispersion simulations may be the same as that used for any subsequent explosion simulation; however, there is a wider choice of CFD codes that can be used for dispersion analysis than are validated for explosion analysis. As CFD dispersion results are not currently used directly in the explosion analysis, the use of separate CFD codes for dispersion and explosion calculations does not incur any significant penalties and is acceptable from a technical perspective.

The disadvantage of using CFD is that it can limit the number of different scenarios that can be analysed and, therefore, methods have been developed to allow interpolation between different cases. However, with the continuing increase in computing power, the effect of this limitation will reduce.

As with any application of complex modelling, it is critical that CFD analysis is carried out by competent and experienced personnel and the guidelines for use of the specific CFD code should be followed. In addition, experienced users are likely to understand when simpler techniques can be used to define or support the scope of any CFD analysis.

4.2.2.1 Use of CFD dispersion results – equivalent stoichiometric clouds

Modelling of gas dispersion using CFD may be carried out to determine the extent of the flammable cloud for purposes not related to the calculation of explosion load (for example to determine if a release can reach occupied areas). In this case, the results of the dispersion results can be used directly.

However, while experimental data does exist for explosions in realistic release scenarios [14], the validation of any methodology to progress directly from a dispersion analysis to an explosion simulation is difficult. Small variations in cloud development can have a significant effect on the explosion simulation [24], introducing considerable uncertainties when comparing experimental data with combined simulations. This is compounded if a time dependent analysis is carried out, with ignition occurring at different times with different flammable cloud sizes and concentrations.

The results from CFD dispersion analysis are, therefore, generally not used directly in CFD or phenomenological explosion simulations. The dispersion results are post processed to define equivalent stoichiometric clouds to be used in the explosion simulation

An equivalent quiescent stoichiometric gas cloud is intended to give overpressures similar to the non-homogenous and turbulent clouds ignited in some full-scale tests.

Hansen [24] describes a parameter called ‘Q5’ that is calculated by the FLACS CFD code [27] during dispersion simulations. To calculate the Q5 parameter the mass of gas at non-stoichiometric concentrations is multiplied by the burning velocity and the volume expansion ratio at the concentration, both normalised to that for a stoichiometric mixture. This process calculates the total mass of gas in the equivalent stoichiometric gas cloud. It is also stated that for very confined modules the burning rate becomes less important and in the case of a fully closed vessel, only the volume expansion filter should be used. GexCon subsequently made a minor adjustment to the Q5 parameter and named the new parameter Q9 [28]. Q9 is now the most widely equivalent cloud parameter applied by FLACS users.

There are other approaches that have been proposed for ‘idealising’ the gas cloud [29, 30]. These approaches include:

1. Use the volume of the cloud that is above the LFL concentration.
2. Use the volume of the cloud that is between the LFL and UFL concentrations (which is the cloud described above minus the volume of the cloud that is above UFL).
3. Use the volume of the cloud that is between the LFL and UFL concentrations converted to a stoichiometric volume.

Tam [29] describes a comparison with experimental data that indicates that Q9 is biased towards under-prediction of the explosion pressures and has a high variability. The use of the volume of the cloud between LFL and UFL, however, had close to zero bias and less variability. Reasons for the better performance of the cloud volume between LFL and UFL are given.

Pappas [31] describes how the complex shape of a dispersed cloud can be represented using a cubic cloud typically extending from floor to ceiling in the module of interest. It is considered that this method will generally give pressures of similar strength for the equivalent quiescent clouds as for the non-homogenous and turbulent clouds ignited in full-scale tests. It is also stated that the explosion overpressure durations may be shorter than for the non-stoichiometric clouds that may in turn affect the structural response.

Representing a dispersed gas cloud of varying concentration as an equivalent stoichiometric cloud clearly introduces uncertainties in the chain of calculations leading to the calculation of the explosion loads. This has a bearing on the accuracy of the overall process that is not easily quantifiable and, depending on what the results are to be used for, questions whether high levels of detail in other parts of the calculation chain are needed or can be justified.

4.3 Determination of explosion loads

This section discusses the methods that can be used to model or estimate an explosion resulting from the ignition of a flammable cloud. The assessment of explosion risks and the relevance to the design process are discussed separately in Section 5.

The methods used to model explosions include correlations, phenomenological models and CFD. It should be noted that the physical processes involved are complex and even with the use of CFD, there are uncertainties in the values predicted. Care should be taken in the use of the simpler methods as the uncertainties can be large and a cautious approach should be applied when interpreting any results.

It is also notable that DNV Offshore Standard DNV-OS-A101 [32] provides ‘bounding’ overpressures. These bounding overpressures represent space averaged peak overpressure values. These values are suggested as the minimum overpressures for design in the absence of any explosion analysis to provide case specific design loads.

4.3.1 Explosion prediction methods and tools

The commonly used methods for predicting gas explosion loads were reviewed by the HSL in 2002 [33]. Though dated to some extent, the comments and conclusions in this study remain relevant. The following summary is based on the HSL review but updated to take account of changes since the review.

Empirical models, based on correlations with experimental data or more detailed computer modelling, are generally usually used to predict far field blast effects outside the gas cloud combustion region based on an estimate of size of the region generating pressure and the severity of the likely explosion. Examples of empirical models include Baker-Strehlow-Tang (BST), Congestion Assessment Method (CAM) and Multi-Energy Method (MEM) [34]. They can be simple and quick to use so they can be a practical design aid but in general the least accurate as they require some judgement in their application and cannot address specific scenarios. They were also mainly developed as tools for use on onshore sites and the calculation of far field pressure effects would be significantly affected by features such as walls between modules on an offshore facility. At best, they should be applied conservatively and only considered as screening tools.

The duration of the pressure profile is also important in terms of specifying the explosion load. Empirical methods can provide an estimate of the duration; however, Hoiset [35] derived a correlation for confined compartments that can be used to estimate the impulse associated with the positive phase of the pressure profile based on the assumption of a triangular pressure-time history with equal rise and fall times. This correlation is based on CFD simulations of a small number of geometries and should only be considered as approximate. The explosion overpressure impulse, I, is given by:

$$I = 0.042P + 6500$$

The positive phase duration, $t+$, in seconds is then:

$$t+ = 0.084 + 13000/P$$

where

P is the peak overpressure (Pa)

I is the impulse (Pa·s)

$t+$ is the positive phase of overpressure duration in the combustion region (s)

Phenomenological methods are simplified physical models that attempt to model the essential physics of explosions. Generally, they represent the actual scenario geometry using a simplified system, for example a small number of interconnected chambers with turbulence generating source terms between them, to represent the fully 3D nature of the real geometry. This can be a reasonable representation of some geometries such as an offshore module but may not be adequate for more complex situations. Phenomenological models typically generate a peak overpressure or a single pressure-time history taken as representative throughout the area under consideration. Some codes can also predict the blast wave that will propagate away from the gas combustion region into the far field. Short run times make this type of model suitable for running large numbers of explosion scenarios. Examples of phenomenological models include CLICHE and SCOPE (note SCOPE is part of the FRED package and CLICHÉ is now incorporated in the DNV GL ARAMAS package and renamed RIPRAP). These models are essentially proprietary.

Phenomenological models do not provide a detailed description of the variation of the explosion load throughout a module or the transient gas flows that can result in a drag load on equipment.

CFD is in principal the most fundamentally based of the methods discussed here and has the best potential for accurate prediction of gas explosion behaviour over a wide range of geometries and explosion scenarios and in both the near and far field. These tools solve the conservation equations of mass, momentum and energy including turbulence and combustion in a large number of relatively small control volumes covering the region of interest. The tools can provide a wide range of information about the flow field and the explosion behaviour at the expense of significant effort required to set up a suitable geometry model and significant computational power requirements.

The numerical grid is typically insufficient to resolve smaller items of equipment and most pipe work. These items must be represented as they are responsible for a large proportion of the turbulence generated during an explosion so they are represented as drag and turbulence source terms within each cell (so called 'subgrid' modelling or porosity, drag resistance (PDR) models).

In practice, therefore, the accuracy and validity is limited by:

- The accuracy of numerical models.
- The underlying empirical sub models for:
  - Reaction zone.
  - Turbulence generation.
  - Turbulence length scale.
  - Turbulent combustion.
- The modelling of flame speeds close to or exceeding the speed of sound, where shocks start to form. In particular, the DDT process is not modelled, though parameters are provided in some cases that indicate when the conditions that might result in DDT are generated.
- The resolution in the CFD grid can result in the external pressure pulse being 'smeared' resulting in an under-prediction of the far field pressures [36].

The suitability of explosion assessment tools should be at least validated by comparison of simulation results with data taken from full scale tests to avoid scaling effects known to exist in gas explosions [37].

The validation process should demonstrate the 'predictive' capability of the proposed tool rather than simply calibrate a result to one set of experiments.

Examples of specialist CFD gas explosion simulation tools include AutoReaGas, FLACS and EXSIM. Development of explosion capability in OpenFOAM CFD environment has also been carried out by Shell Research.

4.3.2 Explosion code selection

The selection of an appropriate explosion model should be based on the problem being addressed. If the analysis is being carried out at an early stage when there is limited detail, or as a screening exercise to determine the potential extent of an explosion problem, then the simple correlation methods applied conservatively may be sufficient.

If more accurate information is required, taking some account of the facility geometry, then the use of phenomenological models may be sufficient. This is particularly where bulk parameters, such as the average loading on module walls, are required. Examples of where this can be appropriate are a QRA or a risk-based definition of global explosion design loads.

Where more detailed information is required in relation to the explosion, such as distribution of the loading across a wall or the drag loading on equipment at specific locations, then CFD is the appropriate tool to use. CFD can be used in all cases; however, it should be recognised that in the early stages of design there is unlikely to be sufficient detail to accurately model explosions and estimates of the likely congestion in the final design will need to be made. This uncertainty may outweigh the benefits of using CFD (see Section 4.3.3).

It should be noted that the modelling of the interaction of combustion and fluid flow in CFD is complex and requires a proper validation. Only CFD packages that have been through a technically valid development and comparison with large and full-scale data should be used. In addition, CFD requires expertise in its application and analysts should be competent in its use.

4.3.3 Practical use of CFD explosion prediction tools

4.3.3.1 Geometry requirements, methods for early project phases

During the early stages of a typical offshore project, only the general layout and location of the major pieces of equipment are known. The level of geometric detail usually increases as the project proceeds as smaller pieces of equipment and objects such as piping and cable trays are defined. For explosion overpressure predictions at each project stage, the likely effects of geometry detail to be added later in the project should be accounted for. If this is not done, it is likely that the calculated explosion characteristics such as overpressure and impulse will increase significantly, as detail is added throughout the project duration. Two possible methods of addressing this have been postulated [38].

- Make allowance for later increases in explosion loads by multiplying the explosion overpressures predicted for a given level of geometry detail by applying a factor for equipment growth (and hence congestion) based on previous project experience.
- Addition of anticipated ‘probable’ congestion into the explosion geometry model to allow for as yet undefined equipment.

Detailed investigation of an integrated deck platform typical of the central/northern North Sea showed that reasonable prediction of the likely final overpressures required the definition of all major equipment, boundaries (decks, TR/accommodation blocks), all piping with diameters > 8”, Primary structure, secondary structure with cross section dimensions > 5” [39]. A follow up study was recently carried out to assess effect of model completeness for a large platform, which confirmed the high sensitivity of explosion overpressures to congestion level and the need to use anticipated congestion [40].

The anticipated additional congestion likely to be added as the design is progressed can be based on historical data for similar previous projects, equivalent equipment with all of its associated pipe work. Several possible measures of the ‘completeness’ of the current geometry model such as the total length of the defined obstacles or various measures of the blockage ratio have also been proposed [38, 40].

4.3.3.2 Recommendations for use

There are general recommendations regarding the use of CFD explosion tools:

- An explosion prediction code with a demonstrated predictive capability for gas explosions should be used. This will require appropriate modelling of flow, turbulence and flame characteristics along with a validation against large-scale experimental data.
- A sufficiently detailed geometry model should be used with explosion prediction models that rely on a detailed geometry model of the facility.

- Uniform stoichiometric concentration gas clouds ignited both centrally and at the edge should be used in explosion modelling due to lack of calibration/validation for non-uniform non-stoichiometric concentration clouds.
- The numerical mesh should be extended sufficiently far from the region of interest to prevent boundary conditions from affecting the simulation results of interest to the project.

In addition to these general recommendations, there are specific guidelines for each CFD explosion tool such as the minimum number of cells to be used in an explosion region. Analysts should be aware of and follow these recommendations when carrying out assessments. Details can be found in the appropriate user and technical manuals.

5 Risk based assessment

5.1 Introduction

Loss of containment events that can lead to fires and explosions can vary significantly in their magnitude and likelihood, with larger releases generally being much less frequent than the smaller ones.

The potential consequences of any release can also vary significantly, with the larger releases having the capability to cause greater harm and damage. Thus, though the smaller releases are more frequent, the larger releases can contribute most of the fire and explosion risk to people and the asset.

If it were always reasonably practicable to design facilities to withstand the worst-case event, then a risk-based approach would not be required. However, the reality is that it is that for offshore facilities, there is almost always a small possibility of exceeding the fire and explosion loads that the structure has been designed to withstand.

Risk based approaches to fire and explosion management are therefore a key part of the design of any new installation as the most cost effective risk reduction can be achieved at this point in the lifecycle.

The application of risk-based methods is also important in supporting decision making in operations, particularly where there is a change from the original design assumptions. This can occur, for example, if a new field development is tied back to an existing facility or a significant change in the number of personnel on board is planned for maintenance activities.

It should be noted that use of risk-based methods is not unique to fire and explosion hazards. Similar philosophies are adopted for other hazards, such as those from wave loading and seismic events.

5.2 Objectives

As already discussed in Section 2.3, OGUK has developed guidance on risk related decision making. In this guidance, the degree of analysis that is considered appropriate to undertake depends on the **decision context**. As the degree of risk, complexity, novelty and stakeholder sensitivity increases, then the level of analysis should also increase. For particularly critical situations, this should be combined with conservative or cautious assumptions where there is a high level of uncertainty.

The guidance provided in this section concentrates on those situations where there is a requirement for ‘engineering risk assessment’, which is decision context B or C in Figure 1. The term ‘engineering risk assessment’ indicates a combination of **engineering analysis**, such as modelling the response to a defined load, and **risk analysis**.

Within a UK context, the primary objective of engineering risk assessment is that it should ensure that risks to people are tolerable and ALARP. Though demonstration of tolerability is generally not at issue, achieving risks that are ALARP can be more challenging for fire and explosion hazards due to the multiplicity of possible outcomes from any release.

The approach to fire and explosion risk assessment for fires and explosions are described in the following sections. The initial discussion focusses on justifying event frequencies that can be used in design to achieve risks that are tolerable and ALARP and how these might be affected once the facility is in operation. The methodologies used for fire and explosion risk assessment in design and operational are then described.

5.3 Terminology

It is an inherent part of any risk-based approach that there is a small possibility of events that can result in failure of protection systems and potential escalation. Examples include:

- Exceeding the design load for safety critical equipment such that it is unable to fulfil a design function that controls the event, resulting in escalation. This could be the explosion load exceeding the design strength of a blast wall or a fire load on critical structural elements sufficient to cause collapse.
- Dispersion of a gas release to areas with a potential to cause ignition, such as air intakes.
- Impairment of an escape route by thermal radiation.

The probabilistic analysis carried out in a risk assessment is mostly associated with the definition of the accident event or the load to be used in subsequent structural analysis. Norwegian standard Norsok Z-013 [1] provides helpful terminology that has been adopted more widely in the industry:

- **Dimensioning accidental event (DAE)** – accidental events that serve as the basis for layout, dimensioning and use of installations and the activity at large.
- **Dimensioning accidental load (DAL)** – most severe accidental load that the function or system shall be able to withstand during a required period of time, to meet the defined risk acceptance criteria. The DAL is normally based on the DAE.
- **Design accidental load** – chosen accidental load that is to be used as the basis for design. The minimum load will be the DAL.

The DAE is essentially a representative event that is used either to define the fire or explosion a design should withstand or to aid operational decision support.

It is noted in Z-013 that the design accidental load may be more severe than the dimensioning accidental load (DAL) based on other input and considerations.

This is an important qualification as the design accidental load could default to the DAL without further regard. Consideration of whether a design accident load higher than the DAL is justifiable is consistent with the requirement in the UK to demonstrate that risks are ALARP.

It should be noted that not all fire and explosion assessments would require the definition of a DAL. For example, it may be that the DAE is defined as flammable gas dispersion to a point where ignition is more likely. The tolerable frequency of this event can be defined without reference to any DAL.

5.4 Risk tolerability

Risk tolerability criteria in this context are often expressed as a maximum frequency of an undesired event (i.e. one more severe than the DAE) that will be tolerated. Examples of undesirable events already discussed are; exceeding the design strength of a blast wall, flame impingement on critical equipment/structures lasting more than, say ten minutes, or the presence of flammable gas at an air intake.

Any risk tolerability criteria will need to be framed by the consequences of events that exceed the DAE. This may include asset damage, potential harm to personnel and, in the extreme, complete loss of the facility.

Asset damage might be tolerated at a higher frequency than harm to personnel and therefore more than one risk tolerability level may be used in assessing a design. For example, Sections 7.6.2 and 7.6.3 refer to design for the Strength Level Blast (SLB) and Ductility Level Blast (DLB) respectively. SLB is primarily associated with minimising asset damage and consequential business interruption, whereas DLB is related to retaining sufficient integrity in a facility to allow personnel to escape to a place of safety.

In relation to the terminology given in Section 5.3, the DLB corresponds to the DAL. As the SLB is not related to safety aspects, it is not considered further here, though the fire and explosion risk analysis carried out for DALs may also be used to define the SLB if required.

5.4.1 Factors affecting tolerable frequencies

It should be recognised at the outset that there is no absolute or accurate measure of how tolerable frequencies should be defined. Tolerable frequencies are, in the context discussed here, an aid to decision making rather than an absolute boundary. There needs to be a logical basis for their definition within the overall process of managing fire and explosion risks; however, it should be recognised that this would involve approximations and simplifications.

The primary objective is to allow decisions on the measures that prevent, control or mitigate fire and explosion hazards to be made in an effective manner that result in risks that are, as well as can be determined, ALARP.

Given that all fire and explosion events have a safety implication, any decision to be made is highly likely to relate to safety critical equipment. Safety criticality is discussed further in Section 8.8.2.

The factors that can influence the definition of tolerable frequencies for fire and explosion loads are described below.

Risk to personnel

The result of any risk management process must be that the risk to all individuals exposed to major accident hazards lies below the upper tolerability limit and is ALARP. In the UK, the upper tolerability limit for risk of fatality to an individual is generally considered to be 10^{-3} per annum for workers [2].

It should be noted that there are several hazards that contribute to the risks to individuals in addition to fire and explosion events, suggesting that the total risk to the most exposed personnel from fire or explosion events should be significantly less than 10^{-3} per annum.

Demonstrating that risks are ALARP always requires that good practice is followed or that an equally good or better option is selected. However, where good practice is not well defined there is a need to carry out a comparison of the benefits provided by a risk reduction measure and the costs of this measure. Where the costs are grossly disproportionate to the benefit obtained, the measure would be considered as not reasonably practicable.

By way of an example, while installation of a blast wall on the boundary of a process module could be considered good practice, the strength of the wall is not defined by good practice. Instead, the performance requirement should be determined by analysis that weighs the cost of increasing the strength against the benefit obtained in terms of risk reduction.

To carry out this analysis for every safety critical element would be onerous and the selection of tolerable frequencies is therefore normally carried out on a more generic basis that is likely to result in a decision that is ALARP.

This is an important issue in that during the design process; there will most likely be very limited opportunity to re-define the performance requirements for many of the key structural elements. The methodology used in deciding the risk based performance requirements should therefore lead the design to a position that is very likely to be ALARP in the first pass through the design.

Survivability

The maximum tolerable frequency of an undesired event will vary depending on the potential consequences of failure and the context of when a safety critical item may be required.

For example, a maximum frequency tolerated for major structural failure due to fire or explosion may be set as once in 10,000 years (10^{-4} per annum). However, this same frequency would not necessarily be applicable to lifeboats as the time when they are required is most likely when the one in 10,000-year load has been exceeded. Lifeboats would therefore need to survive more severe events, otherwise they would always be in a failed state at the very time they are needed. A maximum tolerable frequency of failure may need to be as low as once in 100,000 years.

5.4.2 Justification for maximum tolerable frequencies

As already stated, the DAL is often selected on the basis that it should not be exceeded more than once in 10,000 years, though at times there may be more stringent targets set. It is worth considering why this might be an appropriate approach to achieving a solution that is ALARP and under what conditions.

When available good practice is not sufficient or appropriate, one approach to determine when costs of risks reduction grossly outweigh benefits is CBA. CBA should only be carried out once all relevant statutory provisions are met, for instance providing a reasonable prospect of escape, evacuation and rescue. The following two thought exercises consider relatively simple hypothetical examples for the design of a single module within an offshore production installation for blast and fire resistance.

5.4.2.1 Explosion case

Working in orders of magnitude, if the following broad assumptions are made:

- The number of personnel on board (POB) is 100.
- The remaining life of the facility is 10 years.
- If the DAL were exceeded, then this would escalate the incident to a level where evacuation to sea was required.
- The consequences of the explosion escalation combined with the risks associated with evacuation results in a 10% fatality rate. (Note that the immediate harm caused by the event is ignored as in this case the design decisions are related to preventing escalation.)

Under these conditions, the average number of fatalities, usually called the Potential Loss of Life (PLL), per year resulting from exceeding the DAL is $10^{-4} \times 100 \text{ x } 0.1 = 10^{-3}$. Over the facility life of 10 years, this would give a PLL of 0.01.

Take as an example that it costs over £100,000 to increase the DAL from a once in 10,000 year event to a once in 20,000 year event for the module being considered. In this case, the PLL from escalation/evacuation is reduced by a factor of about two and the implied cost of averting a fatality (ICAF) would be more than £100,000 / 0.005 or over £20 million. An ICAF in excess of £20 million would normally indicate that costs are grossly disproportionate to the benefits.

It is important to also check on the implications to the tolerability of the risk to the individual. If it is assumed that:

- A person has a 10% chance of becoming a fatality in an escalated explosion event that occurs in any hazardous module once in 10,000 years.
- There are, for example, 5 modules with process inventory.
- An individual spends 50% of their time on the installation.

Then the individual risk from escalated explosion events will be 2.5×10^{-5} per year. This would not result in the overall individual risk suddenly stepping into the intolerable level of 10^{-3} per year as if the individual risk was that close to the intolerable level, it would not be possible to demonstrate with any certainty that it was not already above this boundary, independent of any escalation considerations.

In this example, the use of a DAE based on a one in 10,000 year event would be likely to give a design where the risks are both tolerable and ALARP. The DAL from this DAE would be used for all elements of the module where failure can cause significant escalation of the event beyond the module boundary.

Some consideration should be given to the following special cases:

- The cost of increasing the blast DAL may not be significant, particularly if it is a relatively low pressure loading. If this is the case, then the use of a higher DAL should be considered.
- The DAL for frequencies less than once in 10,000 years may not be significantly greater than that for the one in 10,000 year event. Again, if this were to be the case, the lower frequency DAL may be appropriate for risks to be ALARP as the costs of adopting this could again be low.
- Safety critical equipment required for escape and evacuation if the DAL is exceeded needs a reasonable chance of surviving such a severe event.
- If escalation has a much greater consequence in terms of the fatality rate, such as causing a high casualty rate in the accommodation, then an event frequency less than once in 10,000 years would be appropriate.

5.4.2.2 Fire case

The situation for fires is more complex than that for explosions. This is because:

- For jet fires, the size of a fire will be time dependant as once ESD has been completed, the fire will start to reduce in size. Pool fires will be less variable. In addition, the bigger the fire then often the shorter is its duration as it consumes the released inventory faster.
- The thermal load for objects engulfed by a jet fire will be greater than that for those within a pool fire.
- Failure that results in escalation will require exposure to thermal load for a period that varies depending on the nature of the item being exposed to thermal loading.
- Unlike an explosion DAE, which essentially can be considered as affecting the whole module, a fire is likely to be more localised in its effects. Given that the process inventory may not be evenly spread through the module, some parts may be exposed to higher risks than others.

Given the example calculations in the previous section, ensuring that the cumulative frequency of fires in a module that result in an escalation involving additional fatalities and/or the requirement to evacuate the facility is once in 10,000 years or less should give risks that are both tolerable and ALARP.

Again, it should be noted that some elements of a facility might be required to allow orderly escape and evacuation or protect personnel during this process. Such elements, for example the temporary refuge, may be required to withstand longer duration fire loads than defined by the once in 10,000 years criterion.

5.4.2.3 General comments

The previous sections demonstrate how the use of a design frequency of once in 10,000 years can in many circumstances provide risks that are both tolerable and ALARP. It has also been noted that in some cases, more stringent design targets will be required.

Equally, it may also be possible to justify higher design frequencies in some cases. For example, higher design frequencies (and hence reduced DALs) could be justified for a satellite platform bridge linked to the main platform where the satellite platform is infrequently manned. The satellite platform will have a lower number of fatalities in the case of escalation given the low manning and hence DALs based on frequencies above once in 10,000 years may give risks that are ALARP. It is worth considering the potential manning requirements over the platforms lifetime and the impacts on the risk profiles of increased manning, as it is common for the manning requirements to increase over the course of a satellite platform's lifetime as maintenance requirements increase. Often the risk assessments do not reflect the increased manning.

5.4.3 Specific considerations for operational facilities

The considerations in operations are similar to those in design but with the following qualifications:

- Using a once in 10,000 year frequency may no longer be justifiable as the cost of implementing risk reduction measures may be substantially higher. If this risk target is relaxed, however, then it must be confirmed that the individual risk remains tolerable.
- Care needs to be taken when considering combined operations (COMOPS) where hydrocarbons are present. In these cases, there can be complex interactions between the facilities involved (including flotels and drilling rigs), increased POB and a range of escape and evacuation options.
- Where safety critical elements have degraded performance, or are non-functional, it is, de facto, reasonably practicable that they should be re-instated to their original design intent, all things being equal. However, if the design basis is no longer relevant to current operations, for example due to the changing pressures and composition of the produced fluids, a risk assessment could be carried out to determine the most appropriate measures to implement to ensure risks are ALARP. As always in this process, established good practice should be the first reference point.

In an operational environment, the fire or explosion assessment may be required to provide decision support for a specific issue. This could be, for example, to determine the optimum location for a connecting gangway between a flotel and a production platform. In this case, reference to a risk exceedance target may not be required as the analysis can compare different options against each other rather than to an absolute target. The analysis also only needs to be sufficient to demonstrate that the selected option reduces risks to ALARP (this may consider issues other than fire and explosion events).

5.5 Fire and explosion risk assessment

5.5.1 Preliminary considerations

Before embarking on fire and explosion assessment, it is recommended that some thought be given to the objectives of carrying out the analysis, essentially what is trying to be achieved and what needs to be known. This is important as understanding these aspects often defines what needs to be done in any subsequent fire or explosion assessment.

Examples of different objectives are:

- **To ensure the primary structural barriers (walls, floors and roof) of a module do not fail in the DAE for that module**. This requires a definition of what is meant by failure. It is anticipated that plastic deformation would not count as failure. However, if a wall collapses in one area, but the bulk of it remains intact, does this count as failure?

  This has implications for the analysis, as if collapse is allowed over a small area, then the monitoring of the load in explosion simulations may be an average load over the whole wall. Alternatively, if no collapse is allowed, then the pressure loading must not exceed the failure pressure at any point on the wall. This is a more onerous target and would require the explosion analysis to be carried out in a different way.
- **Prevention of failure of large vessels in fire scenarios**. In general, the means of protecting vessels against catastrophic failure when engulfed in a fire is to initiate blowdown to remove inventory and reduce pressures.

  There is a balance between the reducing pressure in the vessel and the reducing strength of the vessel wall given its rising temperature. It may be possible to ensure that the blowdown is designed such that there is no potential for failure even if the vessel is subject to engulfment within a jet fire throughout the blowdown process. However, if this is not practicable, then it may be necessary to examine the likelihood that the vessel is engulfed in a fire for a duration sufficient to cause failure. This would require an analysis of fire scenarios that might affect a vessel, including their likelihood, duration and extent.
- **Prevention of escalation of a fire scenario to a point of structural collapse**. The first step should be to determine what failures in the structure can cause collapse. This is important as if there is structural redundancy then the fire analysis needs to determine when there is simultaneous impairment of multiple elements of the structure. This needs to be understood before the fire analysis is carried out.

  In fact, all failures that can lead to escalation of fire scenarios in a module that could result in further harm or the requirement to evacuate to the sea should be identified. It is generally the combined frequency of these events that should be below the risk tolerability target.
- **Potential for impairment of a gangway connecting a flotel to a production installation**. The first step is to define what constitutes impairment. This is likely to consist of criteria such as the presence of flammable gas or thermal radiation and overpressures above a certain level.

  The tolerable frequency of impairment will depend on the consequences of loss of the gangway and the potential development of the hazardous event that is already taking place on the production installation. The context is that there will be more personnel on the installation than in normal operations and it needs to be shown that the EER provision is adequate. This is likely to require a risk assessment, as would be required under UK regulations [3].

In each case, the understanding of what information is required from the risk assessment will help to define the scope of the fire and explosion analysis. For example, in the last case above, it is possible that only large releases or escalation events could cause impairment of a gangway. A focus on these scenarios may significantly reduce the amount of analysis required.

5.5.2 Methodology

Once the objectives of the risk assessment have been defined, technically suitable methods for the analysis then need be applied. The following gives a description of the important steps in any analysis. It is not intended as an exhaustive review of the topic but to provide an overview highlighting some of the key issues and pointing to relevant references.

Any explicit QRA will require an estimation of the likelihood of an event and the potential consequences. In reality, most assessments will include the analysis of many different realisations of a release scenario, where a ‘realisation’ is a particular combination of parameters such as release size, location and orientation, wind speed and direction, ignition location.

5.5.2.1 Frequency of loss of containment

The starting point of any fire or explosion scenario is loss of containment and any quantitative risk analysis will need to consider the frequency of releases on an installation. Frequency data for process systems, risers and pipelines is generally based on analysis of reported releases in the North Sea. Publications are available that give the results of such analysis [4, 5]. Blowout frequencies are based on industry data collected worldwide.

The data is mostly used to give the frequency of either representative hole sizes or representative release rates. It is important that the range of hole sizes or release rates used gives any adequate approximation of the continuum of possibilities. In this respect, it is important to note that the medium and large releases are often the main contributors to DALs and the risks to personnel, even though they are less frequent than smaller releases. One caveat to this is for HP/HT wells, where small hole size releases can have high consequences and significantly impact DALs.

For operational facilities, there may be specific integrity issues that should be considered, as higher release frequencies may be appropriate.

5.5.2.2 Outflow

To model potential fire and explosion hazards, it is first necessary to calculate the fluid outflow for each hole size. Though the initial flow rate could be used for this calculation, this will be quite conservative. A more realistic approach is to calculate a time dependent release rate that shows the effect of:

- The time taken to detect the release and initiate emergency shutdown.
- Isolation of the process inventory from which the release is occurring.
- Blowdown of the process system, though for larger releases this will have only a small effect on the release rate.

Appropriate and validated models should be used in estimating outflow. Care should be taken for two-phase releases, as the outflow can be particularly sensitive to the assumptions and modelling approach.

5.5.2.3 Ignition probability

An explosion requires the ignition of a gas cloud, which will take some time to develop. This may be anywhere between tens of seconds to hours, though early ignition is most probable. Events that do not ignite immediately, or perhaps within the first few seconds, are typically referred to as 'delayed' ignition events.

Jet or pool fires can ignite immediately, in which case there is little or no time to build up a flammable cloud that could present a flash fire or explosion hazard. Where the ignition is delayed, the extent of any initial flash fire or explosion will depend on the extent of the flammable cloud and its confinement and congestion. In essence, a flash fire is simply an explosion that did not generate any noticeable overpressure.

In any assessment that involves fire or explosion risk, there will be a need to estimate the probability of ignition. Various ignition models have been published [4, 6, 7, 8] and ignition probabilities will generally increase with the size of the release. Some models allow for aspects such as known potential ignition sources or time dependent changes in the ignition probability as electrical equipment is turned off as part of the emergency shutdown process. Most models also provide some indication or guidance on the probability distribution to be adopted for estimating the timing of any ignition. However, it should be recognised that there is very limited data and therefore there is a degree of uncertainty associated with estimating ignition probability, particularly for the more complex ignition models.

5.5.2.4 Consequence modelling

Dispersion, explosion and fire modelling is discussed in Sections 3 and 4. The modelling techniques used should be appropriate to the requirements in terms of decision support. For example, if detailed pressure loading information is required for locations around a facility combined with estimates of drag loading, then CFD explosion modelling will be required. Phenomenological models are more applicable when less detail is required, or the simplifications made in their modelling are acceptable for the analysis being carried out.

The output gathered from the consequence modelling should also be appropriate for the issue being addressed. For example, for a fire analysis, it may be the potential for a target to be engulfed by a flame or the thermal radiation or dose that the target receives during the fire. For explosions, output is generally pressure loading in terms of magnitude and duration and drag loading.

5.5.2.5 Risk modelling

At its most detailed, QRA of fires and explosions will involve potential releases from all isolatable sections on an installation plus risers, pipelines and wells. For each one of these scenarios, there will be factors that can affect the outcome, including:

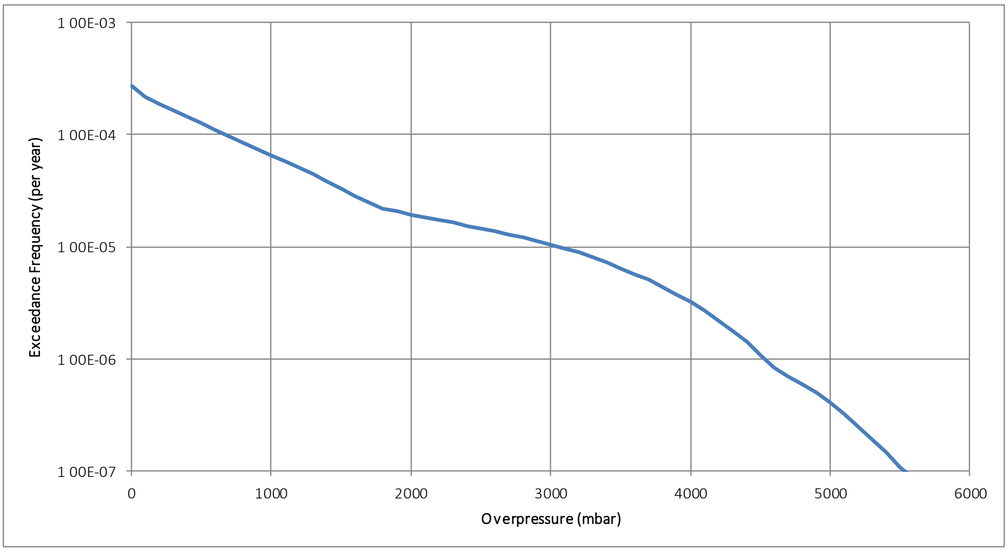
- Release size, type, location and orientation
- Availability and timing of detection, ESD and any blowdown
- Wind speed and direction
- Ignition probability and time
- For explosions, ignition strength and location

The combination of these parameters can produce many possible 'realisations' of any release scenario (typically over 100,000). Whilst it might be possible to explore all the parameter variations using phenomenological models, it is currently not practical for more detailed CFD analysis due to the computational demands. Various techniques have therefore been developed to allow a CFD to be used in risk assessment [9, 10, 11].

If some form of interpolation of results is to be carried out, is important that sufficient variation of parameters is carried out to ensure that the interpolation is not unreasonable.

For design, risk data is generally presented in the form of exceedance curve or plots. This may be a straightforward graph of, say, the frequency of the pressure loading at a given location exceeding defined pressure magnitudes. For fire cases, pressure loading could be replaced by thermal dose. An example of an overpressure exceedance curve is given in Figure 16. It can be seen that design to a one in 10,000 year event (frequency 10^{-4} per year) gives a much lower DAL then the worst case explosion.

Figure 16: Example overpressure exceedance curve



Exceedance data can also be plotted as 2D contours or heat maps or if sufficient information is available in coloured 3D images.

In all cases, it is important that the analysis gives the information required for design and operational decisions and that the uncertainties in the analysis are recognised. Uncertainties are present in even the most detailed and advanced modelling studies.

6 Response to fires

A number of steps are involved in the determination of the response of structures or equipment to fire. These are:

1. Selection of relevant design fire scenarios.
2. Determination of the corresponding design fires.
3. Calculation of temperature evolution within the structural members or items of equipment.
4. Calculation of the mechanical behaviour of the structure or item of equipment exposed to fire.

Two approaches are available for the determination of thermal actions due to fire (steps (1) to (3)); prescriptive or performance based. In the prescriptive approach, nominal fire curves are used (e.g. the hydrocarbon curve). Fire curves are the time-temperature relationships used to control the furnace gas temperature in standard fire resistance tests. They do not represent an actual fire but form the basis by which the fire performance can be evaluated.

In the performance-based approach, simple or advanced fire development models are used to generate thermal actions based on physical and chemical parameters appropriate for the chosen fire scenario. The evaluation of thermal actions using these methods is discussed in Section 3 of this guidance.

This chapter is concerned with the evaluation of the response of structures and equipment to thermal actions from fire. This requires knowledge of the mechanical actions present at the time of the fire, the thermal actions and the properties of the structural material at elevated temperature.

6.1 Properties of common structural materials in use offshore

6.1.1 Overview

In designing steel structures under normal loading conditions (i.e. excluding extreme weather, fires and explosions), structural members are sized such that stresses are below around 60% of the yield stress. This is ensured by the formulations and factors of safety in design codes. As the temperature of structural steel rises, the yield stress and the modulus of elasticity both reduce. At around 550°C, the yield stress reduces to about 60% of its value at room temperatures, and consequently this temperature is often taken as a critical temperature at which failures can start to occur.

Concrete is not used on topsides but there are about 24 platforms in the North Sea with concrete substructures. The top of the concrete is usually several metres below the underside of the main deck, but it can be subjected to pool fires on the sea surface or jet fires from risers. The outer layer of the concrete normally serves to protect the underlying steel reinforcement from corrosion. In a pool fire, this layer protects the steel reinforcement and the bulk of the concrete from the effects of fire, at least for some time. In a jet fire the concrete cover can rapidly be eroded, exposing the steel reinforcement to the effects of the flame

6.1.2 Properties of steel at elevated temperature

Elevated temperature properties of steel that are appropriate for use in structural design are derived from tests known as anisothermal material tests. In these tests, the steel is first loaded and then heated with the load maintained at a constant value. The steel expands due to heat and elongates due to the applied stress. As the steel loses strength and stiffness the rate of elongation increases until a runaway occurs. From a series of such tests at different stress levels, stress strain curves can be derived for a range of temperatures.

FABIG Technical Note 13 [1] contains elevated temperature properties for:

- Carbon Steels:
  - S235, S275, S355, S420 and S460 to BS EN 10025-2 [2], all grades to BS EN 10210 [3] and all grades to BS EN 10219 [4], all of which are covered by the elevated property material model in BS EN1993-1-2 [5].
  - Thermo-mechanically rolled steel grades S460M and S420M to BS EN 10025-4 [6].
  - Quenched and tempered grade S690Q steel to BS EN 10025-6 [7].
  - S355G8 and S460G2 to BS EN 10225 [8].
- Stainless Steels:
  - BS EN 10088 grades 1.4301, 1.4318, 1.4818, 1.4401, 1.4404, 1.4541, 1.4571, 1.4362, 1.4462, 1.4162, 1.4003.

For carbon steel, the rate of loss of stiffness is greater than the rate of loss of strength (see Table 8). Consequently, for the same load level, a buckling failure will occur at a lower temperature than a strength failure.

It can be seen in the table that the strength of steel falls very quickly when its temperature exceeds 400°C. This makes an assessment of the steel temperature very important. At about 500°C, a 10% difference in temperature can lead to a 16% difference in strength.

For some heat-treated and special steels, it may be necessary to carry out tests to establish the elevated temperature properties. This is because the enhancement of properties caused by the heat treatment may be lost if the steel is heated in an accidental fire situation beyond the heat treatment temperature.

The rate of heating is important. The BS EN1993-1-2 [5] data are based on steel heated at about 10°C per minute. This corresponds to a 60 minute fire resistance in a structure where failure will occur at about 600°C. For heating rates between 2°C and 50°C per minute the BS EN1993-1-2 [5] data are reasonable and the effects of creep may be ignored. If the heating rate is faster, the data will be conservative; for slower heating rates the mechanical properties given by BS EN1993-1-2 [5] will be an over-estimate. It should be emphasised, however, that potential heating rates are much faster in fire incidents offshore. In a hydrocarbon fire, flame temperatures can be in excess of 1500°C and temperatures of close to 1800°C have been recorded. The maximum temperature will depend on the size of the fire and the degree of ventilation.

In a hydrocarbon fire, unprotected steel will heat very quickly and will reach temperatures associated with structural collapse in 5 minutes or so.

Concrete loses strength at a broadly similar rate to structural steel but loses stiffness at a faster rate. A good reference is BS EN1994-1-2 [9] (composite construction).

Table 8: Reduction factors for strength and stiffness (BS EN1993-1-2 [5])

Steel Temperature	Reduction Factor for Effective Yield Strength	Reduction Factor for the Slope of the Linear Elastic Range
20°C	1.000	1.000
100°C	1.000	1.000
200°C	1.000	0.900
300°C	1.000	0.800
400°C	1.000	0.700
500°C	0.780	0.600
600°C	0.470	0.310
700°C	0.230	0.130
800°C	0.110	0.090
900°C	0.060	0.068
1000°C	0.040	0.045
1100°C	0.020	0.023
1200°C	0.000	0.000

BS EN1993-1-2 [5] also gives strength reduction factors for bolts and welds at elevated temperatures. As these are not widely available, the information is reproduced in Table 9. The material yield strength reduction factors are also shown for comparison.

It can be seen that both bolts and welds lose strength at a faster rate than structural steel. However, because of the partial safety factors used for normal and fire design this effect is not as significant as it might appear.

Table 9: Strength retention factors for bolts and welds

Temperature	Strength Reduction Factor for Bolts (Tension and Shear)	Strength Reduction Factor for Welds	Yield Strength
20°C	1.00	1.00	1.00
100°C	0.97	1.00	1.00
150°C	0.95	1.00	1.00
200°C	0.94	1.00	1.00
300°C	0.90	1.00	1.00
400°C	0.78	0.88	0.97
500°C	0.55	0.63	0.78
600°C	0.22	0.38	0.47
700°C	0.10	0.13	0.23
800°C	0.07	0.07	0.12
900°C	0.03	0.02	0.06

6.2 Standard fire tests

Fire resistance tests are generally only useful for comparing the performance of different products under constant conditions. Regulations and specifications will often refer to a performance standard based on a fire resistance test. Extrapolation to real fire behaviour can sometimes be misleading. In many cases, for a PFP material, the results of fire resistance tests are all the information that is available and designers must decide whether the heating regime in the test adequately represents the design scenario.

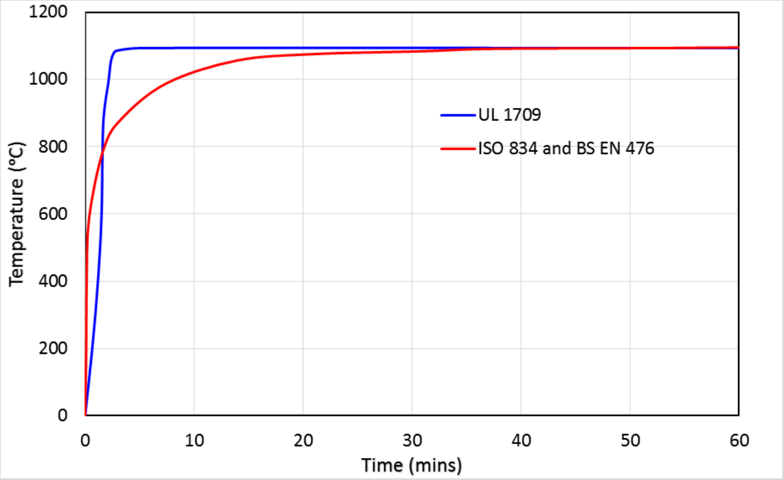
Standard fire tests are typically conducted on single structural members such as a beam, column, or barrier (floor, ceiling or wall) in a furnace environment. Fire-testing furnaces have specific dimensions for each type of structural member/assembly. The furnace temperature is increased in accordance with standard fire time-temperature curves. Based on the duration of the test (time to failure), a fire resistance rating is assigned to the tested member. The time to failure is used to produce fire resistance ratings. This is not an absolute measure of how a particular system will perform in a fire. In different fires, the same system may last longer or shorter depending on the intensity of the fire. ‘A’, ‘B’ and ‘C’ rated fire barriers are normally specified for ships and were originally defined by the International Convention for the Safety of Life at Sea 1974 (SOLAS). They are ratings against a standard cellulosic fire and, as such, are not relevant to this guidance, which is concerned with hydrocarbon fires. ‘H’ ratings are based on hydrocarbon fire tests and are discussed in Section 6.2.1.

More information on firewalls is provided in Section 8.7.3.1.

6.2.1 Standard hydrocarbon fire tests

Rapid temperature rise hydrocarbon fire testing simulates fuel burning at atmospheric pressure that would result from the rupture of a storage vessel, piping, or valve creating a ‘pool’ of burning hydrocarbon fuel. The test standards commonly used (which have similar requirements) are ISO 834 [10] and BS EN 1363-1 [11]. In this test, the furnace temperature is increased to 1100°C in about 20 minutes and then held constant. UL 1709 [12] specifies a standard test used in onshore applications in which hydrocarbon fires are a concern. In this test, the furnace temperature is increased to 1093°C in the first five minutes and maintained at this temperature for the duration of the test. The temperature time curve of the ISO and BS EN hydrocarbon test fires are compared with the UL 1079 fire curve in Figure 17.

Figure 17: Time temperature curves for hydrocarbon fires in fire resistance tests



6.2.2 Jet fire test

Jet fire testing simulates a ruptured riser pipe, vessel, or valve that is releasing hydrocarbon fuel under pressure at sonic velocities. This is by far the most severe type of fire environment as the force of the jet fire produces an erosive effect that must be withstood by the fire protection material. Jet fires also have higher convective and radiative heat fluxes than pool fires.

The ability of a PFP material to withstand a jet fire should be demonstrated by testing in accordance with ISO 22899-1 [13] at an internationally recognised test facility. Preparation of the test samples and the jet fire test are normally witnessed by independent Certification Authorities. The specimens should resemble the intended construction as closely as possible and include, where appropriate, at least one joint. In the test, a sonic release of a gas (0.3 kg s^{-1}) is aimed into a shallow chamber, producing a fireball with an extended tail. Propane is used as the fuel. High erosive forces are generated by release at about 1,000 mm from specimen surface. The method provides an indication of how PFP materials perform in a jet fire. The jet fire test is complementary to furnace testing and the results from both types of test should be taken into account when assessing the effectiveness of a protective system.

Three test procedures for different configurations of passive fire protected components are used:

- Structural Steelwork Test. The structural steelwork test should be used to represent the application of PFP material to steelwork with corners or edge features, for example as in the case of PFP protected I-beams.
- Tubular Section Test. The tubular specimen test should be used to represent the application of PFP material to cylindrical vessels, pipes and tubular sections of up to 0.50 m outside diameter. If the outside diameter is more than 0.50 m but less than 1.00 m, then it will be necessary to perform both the tubular section test and the panel test.
- Panel Test. The panel test should be used to represent applications involving panel materials, for example cast panels used for PFP enclosures around ESDVs and actuators. The specimens should resemble the intended construction as closely as possible and include, where appropriate, at least one joint.

It is essential that the PFP system is tested in accordance with the test method most representative of the specific component or assembly being protected.

ISO 22899-1 [13] adopts a rating system for fire integrity based on ISO 13702 [14], namely ‘Period of resistance (hours)/Type of fire/Critical temperature (°C)’. Hence, for example, 1/JF/400 means that a critical temperature of 400°C will be reached after 1 hour in the jet fire test.

ISO 22899-2 [15] provides background information on the applicability and validation of the jet fire test, further details on testing pipe penetration seals, guidance on the interpretation of the test results and on an optional classification system and guidance on the combination of results from hydrocarbon furnace tests and resistance to jet fire tests.

6.2.3 Failure criteria in standard fire tests

Three failure criteria are used in most standard fire resistance tests; these are: (i) insulation (to limit the temperature rise and fire propagation on the unexposed side of a barrier); (ii) integrity (to limit the spread of fire or smoke to the unexposed side of a barrier) and (iii) load bearing (stability or strength to prevent collapse). Fire spread by loss of compartmentation will increase the likelihood of most types of failure and, therefore, requires particular attention. Compartmentation is achieved through insulation and measures to prevent loss of integrity.

6.2.3.1 Load bearing

Linear structural elements, such as beam, only have to satisfy the load bearing criterion, as they do not form a barrier to the spread of fire. Separating elements that directly prevent the spread of fire (e.g. a bulkhead) have to satisfy all three criteria.

For loaded beams and floors, failure is deemed to occur when the deflection reaches span/20 or, when the deflection is greater than span/30 and the rate of deflection exceeds span2/(9000D) where D is the distance from the top of the element to the bottom of the design tension zone (all dimensions in millimetres) [10, 11]. As well as experiencing large deformations in fire, beams experience large strains. Tests and calculation have shown that strains in excess of 3% are common in the bottom flange of an I-beam in a fire test. For steel beams, the application of any of the deformation criteria will have a small effect as the difference between the time to collapse and the time when any of the criteria might apply is small.

6.2.3.2 Integrity

The ability to maintain the integrity of the element against the penetration of flames and hot gases applies to fire-separating elements. Integrity failures should be rare in fire resistance tests for essentially steel elements. Problems are more likely to occur in actual fires at junctions between elements.

Testing a component in isolation in a fire resistance test may result in acceptance criteria that are simple to achieve. In the test, a combination of good detailing and a suitable thickness of insulation will normally suffice. However, when a component, such as a bulkhead is built into an offshore structure, the interaction between the bulkhead and its boundaries must be considered. Restrained thermal expansion can lead to buckling which may dislodge fire protection material. Boards and thickly sprayed material will be more vulnerable, whilst intumescent coatings will normally be sufficiently flexible. However, intumescent coatings will not protect against loss of insulation. Their activation temperature is generally greater than the limit on temperature rise (140°C).

An important issue is to prevent gaps opening up through which the fire might spread. Awareness and good detailing are probably the best ways to prevent this type of fire spread. Designers should be aware of the likely magnitude of any gaps. In some circumstances, the use of intumescent mastic may be beneficial.

Compartment boundaries will frequently be penetrated by pipework or some form of duct. Maintaining compartmentalisation will normally depend on the performance of a proprietary penetration seal for which there should be suitable test evidence and careful installation and regular inspection.

6.2.3.3 Insulation

The insulation criterion relates to the ability to provide insulation from high temperatures (this also applies to fire separating elements). An insulation failure is deemed to occur when the average temperature rise on the unexposed face of a separating element exceeds 140°C or the maximum temperature rise exceeds 180°C (whichever occurs first). These limits are to prevent combustion of any material that may be close to the unexposed face. Their origins are unknown and, in many cases, the limits may be excessively conservative.

In a fire test, an insulation failure will occur if the insulation is not adequate, or, it may occur because the insulation becomes detached. Often tests on vertical separating elements are carried out on unloaded, unrestrained elements. Results from such tests must be interpreted with care and the systems tested must be carefully installed.

6.3 Failure/Loss of function in fire

6.3.1 Structural failure

Structural failure may occur in the form of excessive deformation or total collapse. The structure has to carry the applied loads at the time of fire but is also subject to thermally induced loading caused by restrained thermal expansion of structural elements. It is also important that the consequences of minor failures on a system are analysed with respect to their effects on other systems. For example, a minor structural failure could lead to the fracture of a pipe or breakdown in an electrical system. Minor residual deformations following a fire that do not impair the function of the component or any other component are not described as failure and may be acceptable.

Table 10 gives examples of failures of the more obvious SECEs which may give rise to escalation and which warrant particular attention.

Table 10: SECE failure or loss of function

System or Equipment Category	SECE Failure or Loss of Function	Performance Standard Requirement (with Respect to Fire Escalation Normally Part of Survivability Characteristics)
Primary structure	Failure is direct cause of major (catastrophic) structural collapse.	• Resistance to defined fire loads for a given duration (for example, a jet fire direct impingement for a duration 15 minutes – say until process pressure is adequately reduced (to limit the reach of the jet flame). The failure would be when the structure could no longer maintain its load within defined deformation limits whose exceedance would cause further breaches of process integrity or collapse of safe areas or evacuation systems. • Residual strength requirement defined.
Secondary structure	Failure allows shifting of load paths and generation of contributory increased loads (ultimately) to primary structure.	• Resistance to defined fire loads for a given duration. • Residual strength requirement defined.
Supporting steelwork for vessels/piping	Failure allows distortion/movement/collapse of hydrocarbon containing vessels and piping with subsequent loss of containment integrity.	• Resistance to defined fire loads for a given duration. • Limits to movement are defined.
Supporting steelwork for equipment	Failure allows distortion/movement/ collapse of rotating equipment/ lifting equipment/ utilities leading to potential loss of containment integrity/ equipment failure/generation of dropped objects/ missiles/ potential loss of power for some safety systems (control, ESD, detection, active protection etc.).	• Resistance to defined fire loads for a given duration. • Limits to movement are defined.

System or Equipment Category	SECE Failure or Loss of Function	Performance Standard Requirement (with Respect to Fire Escalation Normally Part of Survivability Characteristics)
Supporting steelwork for accommodation/ control/ muster areas/TR	Failure allows distortion/movement/collapse of areas of key hazard control and places of safety/embarkation for POB.	• Resistance to defined fire loads for a given duration. • Limits to movement are defined. • Limits to loss of airtight integrity defined. • Residual strength requirement defined.
Supporting steelwork for flooring/ access ways	Failure allows distortion/movement/collapse of access for POB to places of hazard control/safety/embarkation.	• Resistance to defined fire loads for a given duration. • Limits to movement are defined.
Vessels/Main piping	Failure leads directly to loss of containment integrity in hydrocarbon containing vessels and piping.	• Resistance to defined fire loads for a given duration. • Resistance to impact and explosion loads also defined.
Vessel appurtenances/small bore piping	Failure leads to small leaks (loss of containment integrity in hydrocarbon containing vessels and piping) with potential for further fires and explosions.	• Resistance to defined fire loads for a given duration. • Resistance to impact and explosion loads also defined.
Gas detection	Fire from small event may disable systems to detect further escalating events.	• Event size and time delay before triggering defined. • Generally resistance to fire and other hazard loads impractical, continuing function achieved by redundancy.
Fire detection	As above.	• Event size and time delay before triggering defined. • Generally resistance to direct impingement of fire and other hazard loads impractical, continuing function achieved by redundancy.
Blast walls	Blast walls usually have protective requirement with respect to fires as well as explosions, loss of fire resistance integrity following an initial blast will potentially allow spread of fire hazard to other areas.	• Resistance to impact and explosion loads defined. • Resistance to defined fire loads for a given duration following initial events also defined.

System or Equipment Category	SECE Failure or Loss of Function	Performance Standard Requirement (with Respect to Fire Escalation Normally Part of Survivability Characteristics)
Firewalls	Failure leads to loss of control and hence allows unimpeded escalation of the initial event.	• Resistance to impact and explosion loads defined (where possible). • Generally resistance to direct impingement of fire and other hazard loads impractical, continuing function achieved by redundancy.
Active fire protection (AFP) systems	Failure leads to loss of control and hence allows unimpeded escalation of the initial event.	• Resistance to impact and explosion loads defined (where possible). • Generally resistance to direct impingement of fire and other hazard loads impractical, continuing function achieved by redundancy.
PFP systems	Failure leads to loss of mitigation and fire resistance on adjacent systems/steelwork and hence eliminates or impairs any slowing of the escalation from an initial event.	• Resistance to impact and explosion loads defined (where possible). • Resistance to direct impingement of fire and other hazard loads may be impractical, continuing function achieved by diversity within suite of safety systems.
Heating, ventilation and air-conditioning (HVAC)	Failure of closure or redirect aspects of HVAC leads to loss of a control system for unignited gas and products of combustion, allowing unimpeded escalation of the initial event.	• Resistance to impact and explosion loads defined (where possible). • Resistance to direct impingement of fire and other hazard loads may be impractical, continuing function achieved by diversity within suite of safety systems.

6.3.2 Indirect (mechanical) effects of thermal actions

6.3.2.1 Linear expansion

A heated member can exert extremely large forces at its supports that may prove difficult to resist by its supporting structure. Fully restrained steel will yield at a temperature below 200°C; the exact temperature depends on the grade of steel. A beam designed to resist bending has a relatively large axial resistance and, if restrained, may suffer damage even if the heat source is some distance away from the beam. The extent to which axial forces will develop in a structural member forming part of a structure due to a rise in its temperature will depend on the member boundary conditions and the geometry and temperature rise of the structure to which the member is connected.

6.3.2.2 Buckling

Restrained members may buckle to relieve induced compression. For simply supported members this may not cause a problem but, for continuous members, bending resistance at supports may be lost. Buckled steel can cause problems on cooling as the buckling may not be reversed and the steel becomes shorter than its buckled length leading to connection failures. Potentially the tensile force generated is equal to the yield strength of the member. Failures have been observed in both bolted and welded connections and also in the member itself.

Buckling can also occur in any member in compression, when the buckling resistance falls to the level of the applied. The onset of this type of buckling may be exacerbated by axial restraint. However, generally if the supporting structure is capable of exerting compressive restraint, it is also capable of taking up load when a member starts to buckle. This is a complex mechanism that depends on the extent of a fire as well as the structural form.

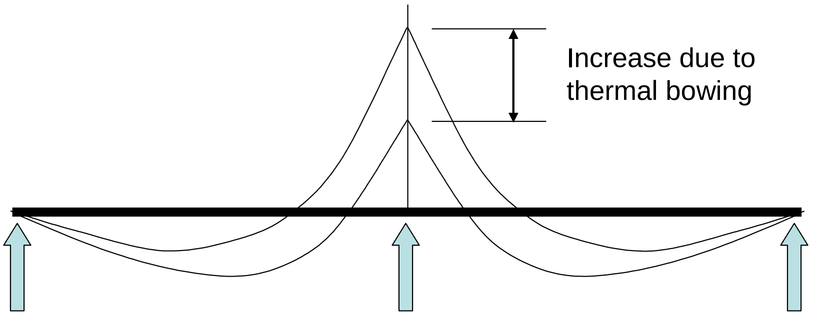
6.3.2.3 Thermal bowing

Any section that is non-uniformly heated will tend to bow. For most sections, the free bowing is a simple function of the temperature difference across the section. A 500 mm deep section, 12 m long, with a temperature difference of 300°C will bow by about 125 mm. A linear gradient will cause no stress in a steel member. A non-linear gradient will cause longitudinal shear stresses to be induced. In some types of partially protected steel beams, compression flanges can, in the early stages of a fire, go into tension.

In a continuous member, thermal bowing will lead to very large induced restraining moments that increase any existing moments (Figure 18). This can lead to failure of connections and buckling of compression flanges and webs.

Deformation caused by thermal bowing can cause disruption of services and affect equipment performance.

Figure 18: The effect of thermal bowing on bending moment in a continuous beam



6.3.3 Effect of load type on failure in fire

6.3.3.1 Bending

Beams will generally withstand large deformations before they are unable to support their design load. In fire tests and actual fires, deformations in excess of span/20 are common.

Continuous beams may be more vulnerable because of the additional thermally induced moments at their supports. This may make lateral torsional buckling of some cross sections more likely and may lead to premature failure of connections.

In many forms of construction, as deformations increase, tensile membrane action may become increasingly dominant. In plated construction, this will supplement the bending resistance and may provide a mechanism for supporting all imposed loads. Often, if a beam supports a plated floor, the beam and plate can act together in fire, although not designed to do so. This can enhance strength and stiffness.

6.3.3.2 Tension

Tension members will lose strength in direct proportion to the degradation in material yield stress. As a tension member loses strength and lengthens, redistribution of its load to structures connected to it occurs. Elongation can be significant. At 550°C, a tension member carrying 50% of its room temperature capacity will elongate by about 1.25%. This Assumes a stress induced component of 0.5% and a thermal expansion component of about 0.75%. For a 6 m long member, this is 75 mm.

6.3.3.3 Compression

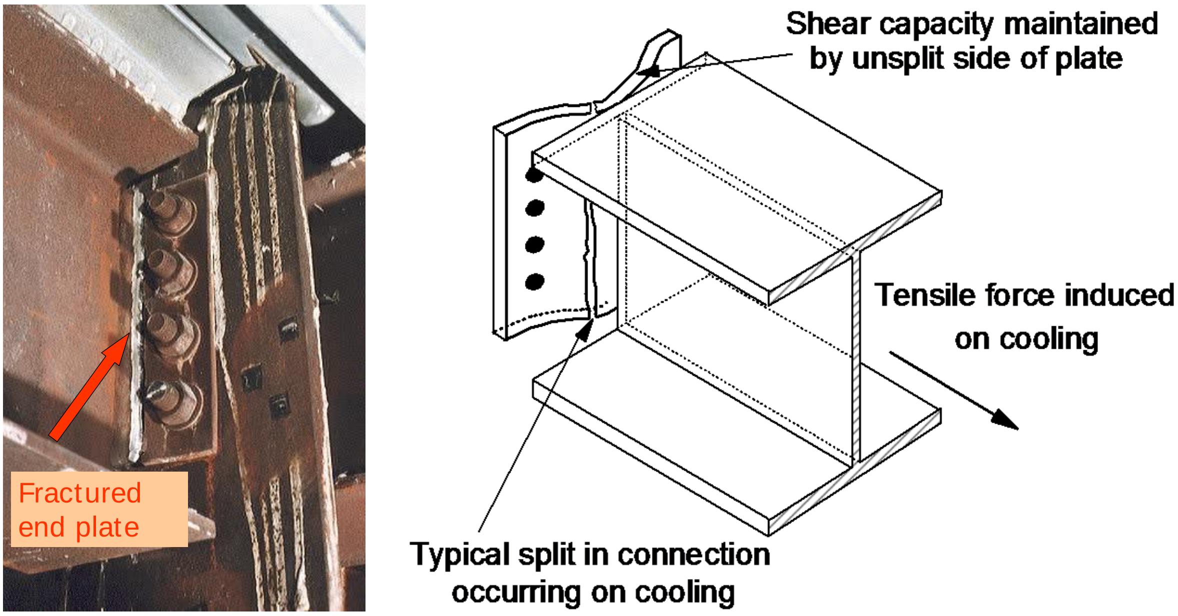
A member in compression will fail at a lower temperature (about 80°C lower than a member in bending at the same load level). This is because the stiffness of carbon steel reduces at a faster rate than its strength.

For most compression members, the applied stress in fire may be increased due to restrained thermal expansion (see Section 6.3.2.2).

6.3.4 Brittle and ductile failure

In a highly redundant structure, failure will be ductile as there will be redistribution of load. However, failures such as those caused by induced thermal stresses on welds and bolts will be brittle but may be followed by an immediate redistribution of load to other parts (see for example Figure 19). The consequences of the failure of large elements in redundant structures need careful consideration. For example, Topsides with significant cantilevered decks, which support the TR at the extremity, are prone to progressive local collapse, especially where critical module support frame (MSF) deck braces are required to support the cantilever. Localised failure due to yielding under fire will in most cases redistribute the gravity loads elsewhere to unaffected areas, except under extreme e.g. riser rupture type scenarios. Thus, as damage and local failures accumulate, the final failure may be sudden as redistribution of load becomes impossible.

Figure 19: Failure of a welded connection on cooling



Source: Photo by permission of BRE

6.4 The structural Eurocodes

The structural Eurocodes are proposed in this guidance to provide the basis for fire design of structures. Although developed for buildings, the rules are readily applicable to topsides structures. This section introduces concepts and parts of the Eurocodes that are relevant to this guidance. It also discusses the Eurocode approach to combinations of actions on structures and particularly, combinations of actions that are relevant to the fire situation. Later sections make specific reference to the Eurocode requirements for analysis and verification of structures subjected to accidental fire events.

The structural Eurocodes are a set of structural design standards, developed by the European standards body CEN to cover the design of all types of structures in different materials.

There are ten separate structural Eurocodes, the relevant ones to this guidance are:

- BS EN 1990 – Eurocode: Basis of structural design
- BS EN 1991 – Eurocode 1: Actions on structures
- BS EN 1993 – Eurocode 3: Design of steel structures

The Eurocodes contain two distinct types of statement – 'Principles' and 'Application Rules'. The former must be followed to achieve compliance; the latter are rules that will achieve compliance with the Principles but it is permissible to use alternative design rules, provided that they accord with the Principles. Within the text of the Eurocodes, provision is made for national choice in the setting of some factors and in the choice of some design methods (i.e. the selection of particular Application Rules); the choices are generally referred to as 'Nationally Determined Parameters (NDP)' and these are given in the National Annex to each part. Each Eurocode is published in several parts and each part is accompanied by a National Annex that implements the CEN document and adds the country specific provisions. Where the opportunity is given in the text of the Eurocode, the National Annex will:

- Specify the value of a factor.
- Specify which design method to use.
- State whether an informative annex may be used.

The guidance given in the National Annex of an EU Member State applies to structures that are to be constructed in that Member State and may differ from one country to another. The National Annexes for the country where the structure is to be constructed should always be consulted in the design of a structure.

In addition, the National Annex may reference other guidance that contains 'non contradictory complementary information (NCCI)' that will assist the designer. As the name suggests, any guidance that is referenced in the National Annex must not contradict the principles of the Eurocode. The Eurocodes omit some design guidance where it is considered to be readily available in textbooks or other established sources. Publications that contain such design guidance may be referenced in the National Annex as NCCI. Additionally, BSI publishes NCCI guidance in the form of 'Published Documents'. These documents are only informative and do not have the status of a standard.

6.4.1 Eurocode symbols

The Eurocode system uses the ISO convention for symbols and subscripts. Where multiple subscripts are used, a comma separates them. Four main subscripts and their definitions are given in Table 11.

Table 11: Main subscripts used in Eurocode terminology

Eurocode Subscript	Definition	Example	
Ed	Design value of an effect.	M_{Ed}	Design bending moment.
Rd	Design resistance.	M_{Rd}	Design resistance for bending.
el	Elastic property.	W_{el}	Elastic section modulus.
pl	Plastic property.	W_{pl}	Plastic section modulus.

For fire design, additional abbreviations are introduced into the subscripts, to distinguish them from the parameters for normal temperature design. The main ones are given in Table 12.

Table 12: Main subscripts used in fire design

Eurocode Subscript	Definition
fi	Property in fire conditions.
θ	Property at elevated temperature θ.
m	Property in fire conditions when member is unprotected.
p	Property in fire conditions when member is protected by insulation.

6.4.2 Basis of structural design

The basis of structural design set out in BS EN 1990 [16] states that the adequacy of structures is to be verified (the Eurocode term used to mean 'checked') using the principles of limit state design and gives the principles for determining actions (the Eurocode term used to describe 'loads'), for modelling to determine the structural effects of actions (the Eurocode term used to describe 'internal forces and moments') and for determining the resistances (the Eurocode term used to describe 'capacity' of a structural element to resist bending moment, axial force, shear, etc.) to those effects.

The basic requirement for ultimate limit state (failure or excessive deformation of a structure or structural element) is expressed as:

$$E_d \leq R_d$$

where

E_d is the design value of the effect of actions such as internal force, moment or a vector representing several internal forces or moments

R_d is the design value of the corresponding resistance

Actions are classified as:

- Permanent actions, e.g. self-weight of structural members and fixed equipment.
- Variable actions, e.g. imposed floor loads, wind loads.
- Accidental actions, e.g. explosion, fire, impact.

The definition of the characteristic value of an action is given for each class of action, in relation to its probability of occurrence. EN 1990 also states that material and product properties are represented by characteristic values. Characteristic values are defined in the relevant material Eurocode parts, either based on statistical values from test results or, more commonly, in relation to values specified in a product standard.

Design values of actions, material properties and resistances are defined in relation to specific partial factors applied to characteristic values. BS EN 1990 gives recommended values of partial factors γ_F applied as a multiplier to the characteristic value of an action and γ_M applied as a divisor to the characteristic value of a material property (member resistance).

The effects of actions depend on the combinations of actions that can occur and BS EN 1990 gives expressions for the effects different combination of actions. A discussion of the methods used in EN1990 for the determination of design values of combinations of actions can be found in [17].

6.4.3 Combinations of actions for the fire limit state

The occurrence of a fire is considered to be an accidental design situation, commonly referred to as the Fire Limit State. The actions to be considered, and the partial factors applied to them, reflect the probability that once a fire breaks out, some variable loads decrease or vanish, e.g. live loading due to evacuation of personnel. The most relevant combination of actions to this guidance is the combination for accidental situations that include fire. Characteristic values of actions are given in the various parts of BS EN 1991. BS EN 1991 1 2 [18] deals with actions to be used in structural design where adequate performance in fire is required. A discussion of these combinations and the factors to be applied to the actions can be found in FABIG Technical Note 13 [1]. Simultaneous occurrence with other independent actions does not need to be considered. However, where particular risks of fire arise as a consequence of other accidental actions (e.g. a fire following a gas explosion), then the overall risk should be considered when determining the overall safety concept of the structure.

BS EN1990 allows reductions in some applied loads in fire reflecting the accidental nature of this limit state. As an illustration of what might happen, consider wind loading. The design case for wind might be for a once in 50 year's gust. During a fire, a structure might be vulnerable for a few hours. For the same level of reliability, the wind load might be only 20% of the 50 year level.

The combination of actions can also include indirect fire actions. These are internal effects that result from the temperature increase of the structural members. Typical indirect thermal actions were discussed in Section 6.3.2. They can arise for a number of reasons, such as differing thermal expansion within statically indeterminate members, thermal gradients within cross sections giving internal stresses or thermal expansion of adjacent members. Design values of indirect actions due to fire should be determined based on the design values of the thermal and mechanical material properties given in BS EN 1993-1-2.

According to BS EN 1991, indirect fire actions have to be considered unless one of the two following conditions is met:

1. If they are negligible or favourable. No specific guidance is given in the Eurocodes on how to judge whether the indirect fire actions are negligible or favourable. A designer will, therefore, have to substantiate this to be able to ignore indirect fire actions.
2. They are accounted for by conservatively chosen support models and boundary conditions, and/or implicitly considered by conservatively specified fire safety requirements.

The recommendations given in various clauses show how (2) above is related to boundary conditions for elements, substructures or global structure. No guidance is given as to what is meant by 'conservatively specified fire safety requirements'. Although not explicitly stated, it seems where a structural element is assessed by reference to a standard fire curve then the indirect action of fire can be ignored. The aim of such element analysis is to represent in the structural model the behaviour of the isolated element in a fire test using a standard fire curve. In such a test (which does not represent the real structure), indirect effects from adjacent members are obviously absent. It is, therefore, not considered warranted to attempt to create a more accurate model by introducing the indirect effects of the fire.

In cases where indirect fire actions are not considered (which may be the case for the analysis of elements or substructures, see Sections 6.5.1 and 6.5.2), the mechanical loads are constant during the fire. The value of the loads determined in the fire at time $t = 0$ does not change during the fire and the effects of actions determined at time $t = 0$ may be considered as constant throughout fire exposure. If a global structural analysis is being performed, the permanent and variable actions are usually considered as constant but the indirect effects of thermal actions (where these are present) are likely to vary during the fire.

6.5 Analysis of structures in the fire situation – the structural model

Structural response analysis is used to evaluate the mechanical behaviour of the structure (step (d) in the four-step approach set out in BS EN 1991-1-2). Structural analysis can be performed on a member by member of the structure, on parts of a structure (structural sub-assemblies) or on the whole structure (global structural analysis). In the latter two cases, current practice is to use FEA except where the structural model is relatively simple. Fire response analysis using finite elements is discussed in more detail in Section 6.5.3.

6.5.1 Member analysis

In a member analysis, an individual member or joint is selected. The applied loads are calculated using the appropriate partial load factors. The end reactions are generally calculated making the same assumptions that were made for the permanent condition. The effects of thermal restraint and any second order or P-Δ effects are ignored. In these conditions, the analysis only accounts for loss of material strength.

For compression members it is normal to consider the possibility that the degree of end-fixity may increase in fire leading to a reduction in effective length. BS EN 1993-1-2 allows the effective length in fire to be 50% of the system length. The reduction has two justifications: First, a column will be constructed as a continuous member and second, it can reasonably be expected that the temperature at the ends will not be as high as at the mid-height position. The method is useful for beams or columns that are not heavily restrained and for simple ties.

The main disadvantages of member based methods are that they do not take into account the effect of the fire on the supports, the development of the fire and its distribution within the structure, nor load shedding and load redistribution that takes place between members within the same frame and between frames. However, almost all real structures contain a degree of redundancy, and simplistic calculations will not provide an accurate estimate of strength.

6.5.2 Analysis of part of the structure (sub-structure)

In the analysis of a part of the structure, that part must have appropriate support and boundary conditions. When carrying out an analysis for part of the structure, the following should be considered:

- The part of the structure to be analysed should be selected such that its interaction with other parts of the structure can be approximated by time-independent support and boundary conditions throughout the duration of the fire exposure.
- Within the part of the structure to be analysed, the temperature dependent material properties, stiffness and thermal expansions and deformations should be taken into account.
- The model of the part of the structure to be analysed should be sufficiently detailed to model the failure modes corresponding to the fire exposure, as well as load shedding and load redistribution.

6.5.3 Analysis of the entire structure – using finite element analysis

In the context of fire design of topsides on offshore structures, the whole topside module or modules but not the topside and substructure together would be analysis for the fire situation. In this type of analysis it is possible to assess the degree of redundancy of the structure beyond first member failure and to determine the manner in which load shedding and load redistribution are taking place.

The use of finite element modelling has become very common in structural fire analysis and there are many commercial general-purpose finite element codes capable of performing such analyses. They can handle large problems, have access to a wide range of element types and solution algorithms and have a wide range of capabilities outside fire engineering. Hence, if a structure is to be analysed for several combinations of actions, this can be done using a single structural model.

6.5.3.1 General good practice

Finite element packages used should have been validated against test data and the engineer using the package should be trained and preferably experienced in the types of analysis being undertaken. Prior to any FEA being carried out, the conceptual model of the structure should be carefully checked and possibly agreed with any potential certification authority. Consideration should be given to the need to include initial imperfections and whether a dynamic option should be included in the analysis. It is important that any analysis includes all non-linear effects (material and geometric) and that the elements chosen can model membrane action where this is likely to arise. The sensitivity of any analysis to the mesh density should be investigated (although not necessarily for each job). Experience has shown that finite element analyses of the same fire and structural scenario using the same software, carried out by more than one group, can produce widely different results. The differences are often due to differences in the conceptual model. The assumptions regarding boundary conditions must be justified. If a part of a structure is being analysed, the boundary condition assumptions regarding restrained thermal expansion can greatly affect results. Element connectivity should also be checked. These are all very important considerations which must be addressed if the results are to be trusted.

In some areas, it may be possible to carry out preliminary 'scoping' analyses to get an idea what answers might be expected from the finite element. Following any analysis, the results should be carefully examined and anything that looks unusual should be investigated. It may be correct or it may be due to an error in the conceptual model.

Compared with an elemental approach (member analysis), any finite element approach based on the same temperature distribution should give more reliable results. However, many finite element models will not properly predict localised behaviour such as connection failure due to the need to refine the mesh density, unless the analyst is aware of the possibility of such failure and has made an allowance for it in the model.

In order for the analysis to give a reliable estimate of structural behaviour, a suitable fire model is required. Often, designers will impose the standard fire (hydrocarbon, cellulosic, etc.) on the structure. This may satisfy regulatory requirements but does not represent reality. In any real fire scenario, the heat flux impinging onto the structure will be different from place to place and will vary in time. Imposing the standard fire will not allow effects due to temperature differences to be modelled.

To obtain an accurate prediction of structural behaviour at a high temperature, it is necessary to consider several factors that are typically excluded under ambient conditions. These include material non-linearity, geometric non-linearity and the variation in strength with time/temperature.

6.5.3.2 Eurocode requirements for advanced models

BS EN 1993 1 2 gives some guidance on using advanced numerical models. The relevant parts are summarised below. The analysis should include:

- The effects of non-linear temperature dependent material properties, including the effects of unloading on the structural stiffness and the effects of cooling;
- The combined effects of mechanical actions, geometrical imperfections and thermal actions;
- Validation of advanced calculation models;
- The validity of any advanced calculation model shall be verified;
- A verification of the calculation results shall be made on basis of relevant test results;
- The critical parameters shall be checked (by means of a sensitivity analysis) to ensure that the model complies with sound engineering principles.

6.5.3.3 Uncoupled and coupled analysis

FEA can be uncoupled or fully coupled. In an uncoupled analysis, temperatures within the structure are calculated for the duration of the fire (or for longer if necessary). The time-temperature results provide the input into a separate structural analysis. This has the advantage of allowing different models and software to be used for heat transfer and structural analysis. Even if the same geometry is used for thermal and structural analysis, the optimum mesh densities for the two analyses are usually different, so adopting an uncoupled approach can improve calculation efficiency and accuracy.

A fully coupled thermal-structural analysis is rarely warranted in fire engineering as there is normally only a weak coupling between heating and structural response. It may be required in certain cases, for example, where the heating of the structure causes a change in boundary conditions or where structural damage changes the exposure conditions to heat. The input data required for the heat transfer aspects of a fully coupled analysis are the same as for uncoupled analysis. However, the chosen elements need to have both structural and thermal degrees of freedom and their meshing must ensure accuracy across both thermal and structural analyses.

6.5.3.4 Static and dynamic analysis

There are two types of structural analysis techniques available for modelling structures in fire by reference to whether physical time is taken into account.

Static analysis

Static analysis is the most common method of analysis of heated structures. Time is used to define the order in which loading is applied, but otherwise has no physical significance or effect on the solution. Therefore, although the order in which actions (structural or thermal) are applied affects the results, the time over which they are applied is arbitrary. Increasing the time period of an analysis does not affect the results, provided the order of load application is not changed. This also means that inertial forces are ignored.

Static analysis of a heated structure assumes that structural loading is constant, while thermal loading varies. This is a good representation of most fire scenarios because the dead and live loads will be present on a structure prior to a fire and remain approximately constant during heating. In such an analysis, structural loads are applied in the first step of the analysis and maintained while thermal loads are introduced in subsequent steps. Thermal loads can be varied over the analysis time.

Static analysis of structures in fire can run into numerical difficulties (convergence problems) when instabilities (e.g. due to buckling) occur. However, used with care they can produce useful results rapidly.

Dynamic analysis

Time is modelled with its correct physical meaning in a dynamic analysis and inertial forces are accounted for. There are two techniques used in dynamic FEA, ‘explicit time integration’ and ‘implicit time integration’. Both can be used for modelling structures in fire.

Explicit dynamic analysis uses the calculated state of the structure at the end of one incremental time step to calculate its state at the next time step. The numerical solution is mathematically stable provided that the time steps used are sufficiently small. For this reason, explicit dynamic analysis of large models can be computationally expensive. Since dynamic explicit numerical models are capable of reaching a solution even if it is not physically meaningful without the convergence problems associated with static analysis, it is recommended that very careful benchmarking is undertaken of such models. This process may include running a secondary static analysis until convergence problems are encountered and comparing the results with those predicted by the explicit dynamic analysis up to the same point.

In implicit dynamic analysis, the dynamic equilibrium equations are solved by direct integration in an iterative manner to estimate the solution at the next time step. This process requires large matrices to be inverted at every time step, which is computationally intensive; however, there is no mathematical limit on the size of time step that may be used in such an analysis. This form of numerical scheme has been less frequently used for structural fire engineering.

6.6 Verification of member resistance

BS EN 1993 1 2 [5] sets out the mechanical resistance and integrity criteria that need to be satisfied when the structure is exposed to fire. Additionally, it defines the design values of mechanical and thermal material properties in relation to characteristic values. The partial factor $\gamma_{M,fi}$ is applied to characteristic values (although, since the value of $\gamma_{M,fi}$ = 1.0 is recommended and accepted by the National Annexes, thermal properties are usually referred to without any designation as characteristic or design values).

The verification of fire resistance is expressed as the requirement, at time *t* during the fire exposure that:

$$E_{fi,d} \leq R_{fi,d,t}$$

where

$E_{fi,d}$ is the design effect of actions for the fire situation; determined in accordance with BS EN 1991-1-2

$R_{fi,d,t}$ is the corresponding design resistance in the fire situation at time *t*

BS EN 1993-1-2 gives simple design models that can be used to determine the resistance of individual structural members subject to tension, compression and bending, as well as combined axial compression and bending. It also provides a critical temperature method. More advanced calculation methods involving sub-assemblies or whole frame analysis is permitted as discussed in Section 6.5.3.

6.6.1 Section classification

All members, which act wholly or partly in compression, are classified in order to establish the appropriate design calculation methods to be used. This is similar to normal temperature design and provides a check on the slenderness of the parts of the cross section that act in compression to assess their vulnerability to local buckling. As the strength and the elastic modulus of steel reduce at different rates in fire conditions, the section classification at elevated temperature will differ from that for normal temperature design. Rather than determine classification at each elevated temperature, the classification is as for normal temperature, using the recommendations given in BS EN 1993 1 1, except that the value of ε for carbon steel (used in the calculation of cross section slenderness) for fire conditions is taken as:

$$\varepsilon = 0.85\sqrt{\frac{235}{f_y}}$$

where f_y is the yield strength at 20°C

6.6.2 Critical temperature method

This is the simplest method of determining the fire resistance of an isolated loaded member in fire conditions. The method can be used only for member types for which deformation criteria or stability considerations do not have to be taken into account. This allows its use for tension members and restrained beams (where the load bearing capacity in a fire situation is directly proportional to the elevated temperature yield strength), but precludes its direct use for both columns and unrestrained beams.

The critical temperature method is also only applicable to steel grades S275, S355 and S460 (and, presumably other steels with a similar or better strength and stiffness retention characteristics).

The critical temperature θ_{cr} of a member is the temperature at which failure is expected to occur for a given load level, assuming a uniform temperature distribution in the member. Its value is determined from the degree of utilisation μ_0 of the member in the fire design situation, according to EN 1993 1 2, clause 4.2, using the expression:

$$\theta_{cr} = 39.19\ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482°\text{C}$$

Determination of the critical temperature for members that are subject to overall instability requires an iterative procedure. This has been done in the UK National Annex to BS EN 1993 1 2 leading to a table of temperatures which are a function of both slenderness and utilisation. The part relating to compression members is reproduced in Table 13.

Table 13: Critical temperatures for compression members according to UK National Annex to BS EN 1993-1-2

Non-Dimensional Slenderness, $\bar{\lambda}$	Critical Temperature (°C) for Utilisation Factor, μ_0					
	0.7	0.6	0.5	0.4	0.3	0.2
0.4	485	526	562	598	646	694
0.6	470	518	554	590	637	686
0.8	451	510	546	583	627	678
1.0	434	505	541	577	619	672
1.2	422	502	538	573	614	668
1.4	415	500	536	572	611	666
1.6	411	500	535	571	610	665

Notes: $\bar{\lambda}$ is a non-dimensional slenderness parameter calculated in accordance with BS EN 1993-1-2

6.6.3 Design resistances of structural members

Design for the fire situation is mainly concerned with preventing collapse before the specified fire resistance period. Large deformations are accepted during a fire and normally they do not need to be calculated in the fire design unless they are likely to give rise to escalation.

The design resistance $R_{fi,d,t}$ at time t is determined assuming uniform temperature throughout the cross section, and by modifying the design resistance for normal temperature design to BS EN 1993-1-1, to take into account the mechanical properties of steel at elevated temperatures (see Section 6.1.2). The differences in the equations for cold design and fire design are mainly because the shape of the stress-strain diagram at room temperature conditions is different from the shape of the diagram at elevated temperature.

The resulting design equations to determine the fire resistance of steel members in accordance with EN 1993 1 2, clause 4.1 are given in [1]. They cover tension, compression, shear, bending (of both restrained and unrestrained beams), and combined compression and bending. More guidance on simplified calculation models can be found in [19].

6.6.4 Verification of member resistance to BS5950: Part 8 [20]

Prior to the implementation of the Eurocodes in the UK, BS5950: Part 8 was the standard used for the design of steel structure subjected to fire. BSI withdrew the standard in March 2010. It is mentioned here for completeness. It dealt with the design of beams, columns and tension members. It also gave some guidance on unprotected steel; however, this was limited to 30 minutes fire resistance in the standard cellulosic fire and would not have been applicable offshore structures.

It gave two methods of assessment for beams. The load ratio-limiting temperature method is largely based on fire resistance test results and is principally for I-section beams. The load ratio is the ratio between the member resistance in fire and the cold, member resistance. The code assumes that the strength of a beam can be characterised by the temperature of the bottom flange and that, in some circumstances, a colder top flange will be beneficial. However, a colder top flange is assumed to be supporting a concrete floor. No guidance is given for beams supporting steel plated floors.

The second method is based on moment resistance. From knowledge of the temperature distribution across the section and the material properties at elevated temperatures, the plastic bending resistance may be computed. This method is useful for unusual sections but cannot be used without knowledge of the temperature distribution in the section. Where a comparison can be directly made, this method is slightly more conservative than the load ratio-limiting temperature method.

For members in compression, the only method given is the load ratio-limiting temperature method and the information is, again, based on standard fire resistance test data. For compression members with comparatively low slenderness, there is a built in assumption that the column will have an effective length in fire of about 85% of the assumed cold effective length.

BS 5950: Part 8 gave simple interaction formulae to allow the load ratio to be calculated for both beams and columns. In a useful annex, it gave guidance on reuse of steel following a fire and what one should look for when inspecting a fire-damaged building.

6.7 Definition and assessment of secondary steelwork

In deciding which structural members need to have their performance checked in fire, the required performance for the structure for each particular limit state must be considered. All primary elements of structure will need to be assessed and will probably require some form of fire protection. A secondary member is one which, for the particular fire limit being considered, will not cause failure of a primary member or loss of compartmentation by its removal. All secondary members require assessment but may not require protection.

For example, a secondary beam, spanning between larger primary beams and supporting a plated floor may be sacrificial in fire. For the fire scenario under consideration, deformation of the floor may be unimportant. A steel plated floor system will often be able to act as a membrane and not require additional support. The secondary beam may not be critical for giving restraint to the primary beam. However, in a severe fire, heat may be conducted along an unprotected beam into the primary beam and thus reduce the fire resistance of the primary beam. For practical reasons it might be better to protect the entire secondary beam rather than simply coating the ends.

Secondary members, which when cold, restrain a primary member may require fire protection to continue fulfilling this function when hot. However, experience has shown that at the reduced applied loads in fire, the restraint may not be necessary. For example, loads may be resisted by membrane action and the restraint may not be required. It does not follow that a member that carries load will always be required in fire. The function of all members should be looked at. Only members that may fail or deform in fire leading to a performance requirement not being met should be considered for protection.

Simple design methods are not able to provide information on whether secondary members require special consideration. Only a full non-linear finite element analysis (NLFEA) will provide this information (see Section 7.8).

6.8 Attachments and coat-back

An unprotected secondary member attached to a protected primary member will allow heat to be conducted into the primary member and may reduce its fire resistance. Most operators' specifications require a length of any attachment to primary steelwork protected with PFP to be similarly protected.

The attachment acts as a heat conductor into the primary steelwork. Hence, it can introduce a localised hot spot at its connection with the primary member. The extent of the hot spot depends on the relative geometries of the primary member and the attachment. The purpose of the coat-back is to reduce heat conducted through the attachment into the primary member and hence limit the extent and severity of the local hot spot. In this way, the potential of premature failure can be avoided. The coat-back length needs to be adequate to achieve this objective.

A joint industry study [21] of the effects of coat-back on the primary member temperature demonstrated the following:

- The required coat back length should be determined based on the local average temperature that can be tolerated in the primary member at the attachment location. As the coat-back temperature increases, this temperature reduces. However, beyond 150 mm, any further reduction is small.
- The ratio of the cross sectional area of the attachment to that of the primary member was found to have a significant influence on the temperature. The ratio of the section factors (H_p/A) has secondary significance.
- The effect of the attachment on the temperature increased with increasing fire resistance period. Thus, to maintain the same temperature in the primary member a longer coat-back length would be required for a 2 hour duration than for 1 hour.
- Within the limits of the study, it was found that the section shape (of both the primary member and attachment) had negligible effect.
- The properties of fire protection material have a small effect on coat-back length.

Guidance on coat-back given in NORSOK Standard S001 [22] states in clause 19.4.2 that:

> *Coat-back (integrity protection) may be required on unprotected structural elements in order to maintain load bearing capacity during dimensional accidental loads. This may be necessary in order to avoid excessive and unacceptable heat conduction into fireproofed structural elements. In general the following shall apply:*
>
> - *Coat-back is required for structural elements with a contact area equal or larger than*
> - *1000 mm^2 per m^2 of fireproofed structural elements;*
> - *Coat-back distance shall be 450 mm, unless documented otherwise.*
>
> *Contact area also includes the part of the cross sectional area inside hollow sections. The coat-back requirements may be deviated from if it can be documented that structural loadbearing capacity is maintained for dimensional accidental loads.*

6.9 Response of process equipment

6.9.1 General

Process equipment and pipework have a much broader variety of response to fires than structures. The response ranges from the simple sagging of a dry pipe to the potential catastrophic explosion of a pressure vessel, BLEVE, or a rupture of hydrocarbon transporting pipe. A key requirement for any design is knowledge of the quantity, composition and properties of the hydrocarbons to be processed and of the associated operating conditions (temperature, pressure, flow rate etc.). This section is primarily concerned with the response of pressurised systems to fire. In a fire, a pressurised system (e.g. vessel, pipeline or heat exchanger) will fail through weakening of the containment material with temperature and time and/or overpressurisation caused by heating up their contents. Generally, offshore systems are fitted with pressure relief systems to prevent overpressurisation and blowdown systems to prevent loss of containment.

The design and protection of piping systems and their support in fire situation is covered by FABIG Technical Note 8 [23].

6.9.2 Failure criteria

In order to know what measures to take, if any, in protecting an object against fire, it is necessary to know the maximum acceptable temperature of the object and the minimum allowable time to reach this temperature. Different references suggest different critical temperatures. Some of those in most common use are summarised in Table 14.

Failure of a steel component will occur at the time at which the superimposed stress exceeds the material strength and/or deformation limit. Knowledge of the time to failure is critical in deciding on the remedial methods to be applied to delay failure. The time to failure of a vessel or pipe work depends on the severity of the fire, the extent and type of fire protection, and the pressure response and can vary between a few minutes and a few hours. The Energy Institute (2003) [24], considered three calculation methods:

- Ultimate tensile stress (UTS) with a safety factor.
- Flow stress (combining UTS and elongation stress).
- Creep rupture stress (where both temperature and time are taken into account).

In theory, the most appropriate failure criterion is the creep rupture strength, rather than the tensile strength since, as the time to rupture goes to zero; the creep rupture strength becomes equal to the tensile strength. However, in view of the complexity of creep rupture calculations (see, for example, Benham et al., 1996 [25]), tensile failure criteria are often used. In severe fires, the rate of temperature rise in the wall above the liquid level or in a gas/vapour only system is very high (of the order of 100 to 200 K min^{-1} depending on the steel thickness) and the material strength falls rapidly once the temperature exceeds 500°C. In these circumstances, where the time involved is very short, the use of UTS may be acceptable if used with an appropriate safety factor.

Table 14: Commonly used critical temperatures

Temperature (°C)	Use	Source	Criteria
550-620	Structural steel onshore	ASFP, 2002 (BS 5950)	Temperature at which fully stressed carbon steel member loses its design margin of safety.
427	LPG tanks (France and Italy)	ISO 23251:2006 (1997)	Based on the pressure relief valve setting.
400	Structural steel offshore	ISO 13702, 1999	Temperature at which the yield stress is reduced to the minimum allowable strength under operating loading conditions.
300	LPG tanks (UK and Germany)	LPGA CoP 1, 1998	Integrity of LPG vessel is not compromised at temperatures up to 300 ºC for 90 minutes.
200	Structural aluminium offshore	ISO 13702, 1999	Temperature at which the yield stress is reduced to the minimum allowable strength under operating loading conditions.
180	Unexposed face of a division	ISO 834 BS 476	Maximum allowable temperature at only one point of the unexposed face in a furnace test.
140	Unexposed face of a division	ISO 834 BS 476	Maximum allowable average temperature of the unexposed face in a furnace test.
45	Human skin	Hymes et al., 1997	Pain threshold.
40	Surface of safety related control panel	ISO 13702	Maximum temperature at which control system will continue to function.

However, BS 7910 (1999) [26] suggests that the proximity to plastic collapse should be assessed by determining the ratio of the applied stress to the flow stress, where the flow stress is defined as the average of the yield and tensile stresses. Use of a flow stress of the average of, say, the 0.2% elongation stress and the UTS would be a more conservative measure. However, if the rate of temperature rise is much slower, e.g. with a system protected by PFP, it is more appropriate to use the creep rupture stress. No consensus was reached within the Energy Institute working group on which method of assessing stress is the most appropriate for response to severe fires. It was stated that the ambiguity remains because of the lack of validation data. Offshore vessels tend to be of a more complex design than storage vessels and will have stress raisers such as:

- Different thicknesses of material.
- Inlet and outlet connections with constraining piping, manways, etc.
- Different types of weld materials and configurations.
- Reaction forces during emergency depressurisation.
- Vapour-liquid interface.

The Energy Institute states that it is not clear which of these features are critical in assessing failure or to what degree, if any, current failure criteria are conservative. Experiments are required to assist in the validation of models intended to assess such features. Unless the failure criteria are properly set, it is difficult to see how time to failure or realistic blowdown rates can be properly set.

Data from jet fire trials (170-190 kW m^{-2} incident heat flux) on pipes pressurised with nitrogen to 85 to 90% of their design pressure endeavoured to take the pipes to failure and determine their failure criteria. The modelling of the heat transfer to the pipe considered radiation from the flame and convection from the hot combustion products. This found good agreement with the measured values for small pipes but found that the model overestimated the temperatures above 600°C for 250 mm pipes. It was found that pipe failure was adequately predicted by comparing the equivalent stress (von Mises) with the UTS. However, it was noted that the pipe corrosion allowance should not be used when making the calculations and that good high temperature UTS data was needed. Hekkelstrand and Skulstad (2004) [27] have incorporated these results in the latest edition of their guidelines. They imply that the method may be applicable to pressure vessels containing vapour and liquid but the complexities identified above are not explicitly considered. They also provide data on the high temperature properties of steels. Data are also available from Burgan (2001) [28] and Billingham et al. (2003) [29].

Following reviews undertaken by SCI, NLFEA permits the rupture calculations of a piping system to be based on more accurate methods that account for the reserve strength inherent in many design codes. It also overcomes the approximations that have been identified with the use of simplified methods.

6.9.2.1 Link between engineering acceptance criteria and QRA

As implied by the above, the link between engineering acceptance criteria related to pressure systems and QRA may be made using the following approach:

- Rule sets in a QRA are set to reflect the standards to which safety critical systems are to perform, e.g. no escalation of the initial fire event in an area.
- This rule set assumes that isolation and depressurising systems, and a dedicated deluge cooling system are functional, available on demand and survive the initial fire (performance standards).
- The systems are designed to meet the normal engineering acceptance criteria for stress, deformation, temperature, etc.
- DALs are determined for the systems whose risk, calculated by QRA, exceeds the risk based performance standards.
- The pressure systems are redesigned to resist the DALs.

Before formal industry guidance could be given on such links, guidance is needed on the rule sets to use in QRA, the determination of DALs and appropriate engineering acceptance criteria.

7 Response to explosions

7.1 Overview of explosion response

This section deals with the assessment of structures, piping and SECEs to explosion loads. It uses a design philosophy discussed in [1]; the latter also provides a review of research into structural response to explosion loads performed since publication of the Interim Guidance Notes [2].

Many structures are designed to resist uncertain explosion loads by calculating the capacity of the structure and demonstrating robustness in the structure as reflected in an ‘insensitivity of response to variations in load’. This approach is to an extent scenario independent and may give added protection against unidentified scenarios and in particular combined fire and explosion events. Achieving structural robustness requires a ductile response and prevention of premature sudden failure (e.g. by buckling or shear). Adequate connections to adjoining members are also important for achieving robustness in order to redistribute load and enable the structure to mobilise its ultimate capacity. Robustness ensures that the structure has the ability to absorb some of the uncertainty in the loading to which it may be subjected.

An explosion event on a topside structure is conceptually analogous to the extreme loading caused by an earthquake due to the small probability of occurrence. Many of the concepts used in design for earthquakes [3] such as attention to connection details and ductility requirements apply equally to the design of topsides to resist explosions. For earthquake design, it is common to consider two design load cases:

1. A frequent earthquake with low seismic forces: the structure or equipment should remain undamaged when subjected to forces from such earthquake. For the structure, this is essentially a serviceability check and the structure must remain elastic.
2. A strong earthquake with a low probability of occurrence: the structure can sustain damage but overall collapse should not occur.

By analogy with this approach, two levels of explosion loads are recommended for explosion assessment. The SLB and the DLB obtained from consideration of exceedance curves or from the use of derived nominal overpressures. A DLB typically corresponds to probabilities of exceedance of 10^{-4} whereas a SLB corresponds to probabilities of exceedance of 10^{-2} [4].

The ‘robustness’ approach is valuable and should be considered in addition to the more rigorous probabilistic methods to load determination described in this guidance.

Due to the extreme nature of the DLB loads, it is essential to prevent overall structural collapse. Local failure may be tolerated as long as it does not lead to an unacceptable escalation through progressive collapse, leakage of inventory or failure of SECEs.

This places considerable emphasis on the requirements for structural and equipment robustness, i.e. ensuring that systems can absorb significant amounts of energy and be able to redistribute internal forces via the provision of adequate alternative load paths.

7.2 Information required for explosion response calculations

7.2.1 Information from the explosion load simulations

For High risk installations, information will include:

- Pressure exceedance diagrams for each combustion zone.
- Identified SLB and DLB load cases – these should include spatial distributions of peak overpressure and overpressure-time histories at critical locations.
- SECEs and their criticality levels.
- Dynamic pressure exceedance curves for SECEs of criticality 1 for the DLB with time histories of dynamic pressures at these locations.
- Dynamic pressure exceedance curves for SECEs of criticality 1 or 2 for the SLB with time histories of dynamic pressures at these locations.
- Other overpressure and dynamic pressure information for significant scenarios with similar frequency, where the loading pattern differs appreciably from the design explosion events. If this is not available then a range of likely durations should be supplied.

If exceedance curves are not generated then the probabilities associated with the design explosion events should be available. If time histories are not supplied, load durations and general shape of the load-time histories should be supplied.

Low and some medium risk installations will only require the information for the DLB explosion loads.

A comparative assessment method may be used drawing on past experience from a demonstrably similar structure geometry and scenario. The nomination of a typical installation to represent a fleet of platforms is acceptable.

7.2.2 Other information from non-structural disciplines

The project should also supply:

- High level and system specific performance standards for evaluation of the results of the assessment.
- Layout drawings, including process, escape routes, muster areas, the TR, the SECEs and their support structures.
- Any structural drawings and the location of tall structures, which may become a hazard in the event of escalation.
- Details of the assumptions for detection, control and mitigation systems: location and required availability.
- For dynamic response analyses, the location and masses of all major items.
- Further exceedance curves will be required from the explosion specialists for dynamic pressure loads to enable the dynamic pressure loading on pipework to be developed.

In order to determine the loading on large items of equipment or vessels, the required items can be identified to the explosion specialist for direct load extraction from the CFD model for various explosion scenarios. Alternatively, a less accurate, but less time consuming method for the explosion specialist, is to provide generalised pressure-time histories for the equipment locations, together with the speed of travel of the pressure wave. The structural engineer then determines the maximum pressure difference between locations of known separation, having determined the time taken for the wave to travel that distance.

If the general level of dynamic pressure loads is not known then it is acceptable to take a load equal to 1/3 of the smoothed peak overpressure at the location for loads on the relevant SECEs and piping. The duration should be chosen so that the impulse is matched to the positive phase of overpressure trace. This load must also be applied in the reverse direction. In open areas, such as the decks of floating production, storage and offloading (FPSO) vessels, these loads should also be applied in the vertical plane.

7.2.3 Explosion load considerations

Design explosion loads represent only one of many scenarios and the reliance on a particular overpressure time history or spatial distribution of overpressure is not advised.

That the detail of a given load distribution is only one of many possible scenarios also implies that reliance should not be placed on the apparent result that some parts of a blast wall for instance seem to receive less load than others; a different ignition point may give rise to a different distribution of load. It is, therefore, not acceptable to design adjacent areas to different pressures without justification.

The structural engineer should develop the idealised pressure-time histories for various pulse durations. The aim is to capture the range of dynamic response of the various components of the system to be designed or assessed. Preferably, a representative range of overpressure time histories can be directly used in the analysis if these are available.

If a range of pressure time histories is not available then extrapolation of the range of durations supplied should be investigated. The peak pressure/duration relationships in Section 4.3.1 may be used to estimate the peak overpressure for shorter duration loads. The peak-averaged overpressure is plotted against impulse by Hoiset et al [5].

The design overpressure of a panel will need to be greater than that for a section of a blast wall, which will in turn be less than that for a whole wall. The pressure disturbance is of finite extent relative to the target and hence the averaged pressure will vary with target dimensions. The explosion load specialist may supply a lower level of design load for an extended structure (deck or wall) than for a blast wall; there are simple methods for deriving scale factors [6]. The approach should be applied with care as the direction of travel of the overpressure pulse relative to the target affects the way the pulse is reflected. The approach is suitable for large deck areas or if sufficiently detailed information on the loading pattern is available.

In modelling the response of a structural frame, it is conservative not to model the cladding or plate as the shear restraint from such surfaces may be overestimated. The overpressure load on a plate may be applied directly to the bounding members of the plate using the ‘tributary area method’. For example, the loads on a square plate may be applied to the bounding framing members with one quarter on each; for a rectangular plate, the members on the long edges would receive a load proportional to the triangular area joining the edges with the plate centre.

7.3 Response regimes

The response of a structure to a dynamic load is commonly characterised by the ratio of the load duration, t_d, to the natural period, T, of the structure. This is also referred to as the impulse duration ratio. Depending on the value of this ratio, three response regimes are defined:

- Impulsive – the structure may resist a very high peak pressure (greater than the static capacity of the structure) provided that the duration is sufficiently small
- Dynamic – the response is sensitive to the characteristics of the pressure-time history, or
- Quasi-static – the response is governed by the peak pressure and the rise time of the pressure relative to the fundamental period of vibration.

Table 15 is a modified version of that given in the IGN [2] to reflect more recent work published in NORSOK N-004 [7] and summarises the influence of the loading characteristics on response in the three regimes. The impulse duration ratios at the impulsive to dynamic and dynamic to quasi-static boundaries have been changed from the 0.4 and 2.0 values given in the IGN.

Table 15: Regimes of dynamic response

Parameter	Impulsive $t_d/T < 0.3$	Dynamic $0.3 < t_d/T < 3.0$	Quasi-static $t_d/T > 3.0$
Peak Load	Preserving the exact peak value is not critical.	Preserve peak value – the response is sensitive to increases or decreases in peak load for a smooth pressure pulse.	
Duration	Preserving the exact load duration is not critical.	Preserve load duration since in this range it is close to the natural period of the structure. Even slight changes may affect response.	Not important if response is elastic, but is critical when response is plastic.
Impulse	Accurate representation of impulse is critical.	Accurate representation of the impulse is important.	Accurate representation of impulse is not important.
Rise Time	Preserving rise time is not important.	Preserving rise time is important; ignoring it can significantly affect response.	

This table assumes that there is some identifiable natural period for the structure, which indicates that a single degree of freedom (SDOF) idealisation of the structure is possible. Multi degree of freedom (MDOF) systems will have a number of modal periods associated with them, although it is often possible to identify a mode or shape of response associated with each modal period.

7.3.1 Explosion load simplification

7.3.1.1 Equivalent static load

During early design stages, the use of equivalent static explosion loads is generally acceptable to allow progression of the primary structure design using a global static overpressure. A dynamic amplification factor (DAF) is used to transform a dynamic peak load into a static load with the same effect on the structure as the dynamic load. For long explosion times and in case of an idealized triangle shaped shock wave load, the value of DAF approaches its limiting value of 2, which means that, if the load is applied statically, it must be doubled in order to result in the same deformation as that produced by the dynamic load.

A DAF, γ, should be calculated for all loaded members such that the equivalent static load, L_{static}, is related to the peak dynamic load, L_{peak}, by:

$$L_{static} = \gamma\, L_{peak}$$

For single structural components γ may be as much as 2. For typical large structures such as module and topside structures, the natural periods are likely to be longer with DAFs less than one.

An equivalent static load may be obtained from consideration of the modes of response of a structure and by choosing the mode (and modal period) corresponding closely to the expected shape of the response (if this is available). A DAF may then be calculated for this form of response. Another technique is to perform a simplified dynamic analysis and find an equivalent static load distribution that gives similar displacements to the peak dynamic response. This only applies for elastic response but may enable code, utilisation or unity checks to be performed using conventional software.

The DAF obtained for a large structure and the appropriate design load may not be applicable for member or local checks.

For plastic deformations, the DAF is of limited use because a static load that causes yielding would deform the structure without limit. Where plastic deformation occurs, a time history simulation may be used to estimate the DAF including plastic response using Biggs method described later in Section 7.7.6 or similar analysis.

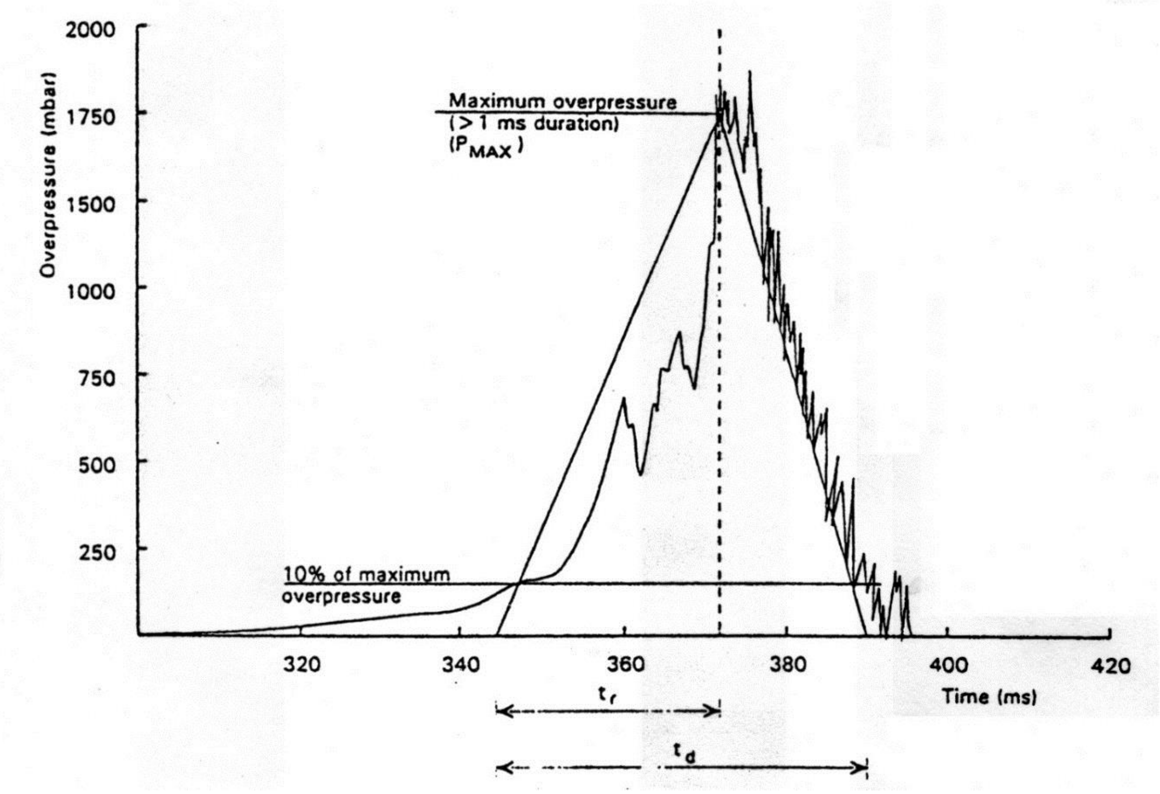
7.3.1.2 Positive phase triangular pressure pulse

For some design applications, a simplified form of the pressure-time history is required. The usual method is idealization of the pressure time history into a triangular form with a positive phase only; Figure 20 [2] shows the conventional idealization of a pressure trace.

For determination of deck response to an explosion from below, it is important to represent the negative phase of the loading to enable the calculation of rebound.

This form is not characteristic of far field blast waves outside a compartment. A typical trace for this case is shown in Figure 14.

Figure 20: Idealised pressure trace for a hydrocarbon explosion



The single peak idealization shown in Figure 20 will not apply when external explosions are involved or when there are two paths to the observation point or in some cases of explosions in the moon pools of FPSOs. There are also concerns that the sharp changes in slope in the idealization introduce spurious frequencies into the exciting force and that it is preferable to use the original pressure traces from CFD or use some spectral approach. Published guidance [8] discusses the accuracy of various methods of idealization of pressure pulses.

7.4 Material properties for explosion response

7.4.1 General

The expected large deformations resulting from an explosion and the dynamic nature of explosion loading mean that strain rate and strain hardening of the material may occur locally. A brief summary is presented here; more detailed information is available in [9] and [10].

7.4.2 Static material properties

7.4.2.1 Overview

In a design or assessment project, if detailed and precise material data are available, potentially a more economical design can be achieved. However, in most design situations the engineer will typically have to rely on generic data specified in the relevant standards. In the special case of brownfield projects, mill certificates for the employed steels should be available. As a minimum, these certificates will contain useful experimental results obtained from tensile coupon tests on the yield strength, the tensile strength and the rupture elongation of the steels.

It should be emphasised that when performing a structural analysis the materials are often assumed to have a limiting strain well below their fracture strain. The reason for this is partly to allow for deficiencies in the adopted analytical modelling tools, and partly to allow for variations not explicitly covered in the geometric and physical description of the structure.

As an example, the influence of specified tolerable variations in the dimension and mass of the structural components as well their alignment are seldom incorporated into the analytical model. In addition, local buckling of compression elements and localised necking of tension elements are in general not automatically captured, except by the most sophisticated and detailed of the analytical tools. According to the IGNs [2], the limiting strain can be set to 5% for a member in tension as well as for a member in bending or compression with a Class 1 cross section.

7.4.2.2 Carbon steel

The quasi-static stress-strain curve for a typical structural steel specimen tested in accordance with standard tensile test procedures, such as those described in BS EN 10002-1:2001 [11] is typically characterised by four distinct phases:

- From the onset of loading, until reaching the upper yield stress, the stress-strain behaviour of the specimen is nearly linear elastic with a modulus of elasticity of about 205,000 N mm^{-2}.
- Thereafter, it follows a rather sudden stress drop down to a lower yield stress…
- Where it remains for a while as the deformations continues to develop, until…
- Strain hardening to rupture.

Stress concentrations and welding both have a tendency to reduce if not remove the upper yield stress. However, for the purpose of designing connections and supports against dynamic loading, ignoring the upper yield stress could prove unsafe. By contrast, when designing the individual structural members it is safe to ignore the upper yield stress.

The yield plateau, which typically terminates at strains at least 10 times larger than the initial yield strain, is followed by a phase of strain hardening at a continuously diminishing rate until the ultimate stress-strain point is reached.

The mechanical properties of structural steels used in the fabrication of fixed offshore structures are given in material standards [12]. This standard specifies the requirements for steel grades S355, S420 and S460. These steels are all suitable for installations in the North Sea sector.

Typical limiting values for some of the mechanical properties specified in BS EN 10225 for grade S355, S420 and S460 steel are listed in Table 16. It should be noted that the minimum yield strength R_{eh} refers to the upper yield strength. The tensile strength R_m is given in terms of an upper and a lower limit, and the ductility is given in terms of a minimum rupture strain A^f. The rupture strain is measured over a gauge length of $5.65\sqrt{S_0}$, where S_0 is the original cross sectional area of the test piece.

Table 16: Mechanical properties typically specified for structural offshore steels

Name	Minimum Yield Strength, R_{eh} (N mm^{-2})	Tensile Strength, R_m (N mm^{-2})	Minimum Rupture Strain, A^f (%)
S355	355	470- 630	22
S420	420	500-660	19
S460	460	530-720	17

It should be emphasised that the actual yield strength of steel is frequently significantly larger than its guaranteed minimum value. In the case of high quality offshore steels [10] the upper yield strengths have been found to be up to 26% larger than their guaranteed value, with an average of about 13%. Such differences between the guaranteed and the actual yield strength need to be taken into account when estimating the magnitude of the forces transferred through joints into the supporting structure.

7.4.2.3 Stainless steels

Compared to carbon steel the stress-strain curve for stainless steels is characterised by a smooth rounded response with no definite yield point. In situations where the yield phenomenon is absent, the yield strength should be replaced with the 0.2% proof strength, $R_{p0.2}$. Another major difference in the mechanical performance at ambient temperature between the two types of steel is the greater ductility of stainless steel.

Table 17 lists typical values for the mechanical properties of various stainless steels covered by [13]. As is the case for carbon steels, the actual yield strength, here taken as the 0.2% proof strength, is usually significantly larger than the minimum specified in the standard. For the experimental test series on which the data in [10] is based, the measured proof strengths were on average observed to be 28% larger than the specified minima.

Furthermore, the mechanical requirements given in the table refer to material in the annealed condition. Thus in situations where the structural elements will be subjected to some degree of cold forming without a subsequent heat treatment, the proof strength in the work hardened zones needs to be adjusted upwards.

Table 17: Mechanical properties typically specified for stainless steels

Name	0.2% Proof Strength, $R_{p0.2}$ (N mm^{-2})	1.0% Proof Strength, $R_{p1.0}$ (N mm^{-2})	Tensile Strength, R_m (N mm^{-2})	Minimum Rupture Strain, A^f (%)
1.4404 (316L)	220	260	520-670	45
1.4401 (316)	220	260	520-670	45
1.4362 (2304)	400	-	630-800	25
1.4462 (2205)	460	-	640-840	25

Strain hardening should always be accounted for when designing for the dynamic reaction forces, whereas it can be safely ignored when selecting section sizes.

7.4.3 Strain rate effects

It is well known that the stress-strain characteristics of steel depend on the rate of straining, and that, at least until the onset of strain softening, an increase in the strain rate increases the stresses corresponding to given strains. The more precise effect that high strain rates have on the stress-strain characteristics of a given steel grade is a complicated function of its temperature, chemical composition and internal microstructure. However, in general it is the case that the more the steel can be strengthened by heat treatment or cold working, the more sensitive its mechanical behaviour is to an increase in the strain rates.

Strain rate sensitivity is traditionally expressed in terms of the dynamic increase factor (DIF). For a given strain rate and a given material property the DIF is defined as the ratio between the values of the material property measured under dynamic and quasi-static loading conditions (strain rates of 2.5×10^{-3} s^{-1}). Consequently, the tested value will typically be about 8% larger than the long term yield strength. For typical steel structures, the strain rates associated with hydrocarbon explosions will seldom exceed $1\ s^{-1}$.

In general the dynamic testing of steel specimens has shown that the elastic modulus is unaffected by strain rates, and that the strain rate sensitivity decreases with an increase in the plastic strain. It is also generally accepted that the strain rate effects are the same whether the material is loaded in tension or compression, and that the DIFs are isotropic in nature.

Although an increase in the rate of straining reduces the fracture toughness of steel it is unlikely that the strain rates associated with hydrocarbon explosions will significantly reduce the fracture toughness of the high quality structural steels used for offshore installations.

Design data on the effects of strain rate on the properties of common offshore carbon and stainless steels can be found in reference [10].

It should be mentioned that the strain rates vary both spatially and temporarily within a structure. Thus, when performing a NLFEA it is necessary to know the complete stress-strain behaviour at all encountered rates. Likewise, it is assumed that all conclusions regarding the uniaxial stress state can be generalised to the multi-axial stress state.

7.4.4 Strain hardening

Strain hardening may be taken into account for tension members and class 1 sections by taking design strength to be the ultimate strength divided by 1.25 [2]. This effect should not be considered when designing supports against reaction forces.

It is, however, necessary to demonstrate that the strains are high enough to mobilize the benefits of the strain hardening.

The following groups of structural members may sustain high plastic strain without losing strength from local or overall buckling:

- Members in axial compression or in bending and axial compression whose slenderness ratio does not exceed 15 and whose cross sections comply with the criteria for Class 2 sections.
- Members in bending whose cross sections comply with the criteria for Class 2 sections and whose slenderness ratio (λ) does not exceed certain values.

7.5 Structural performance standards

7.5.1 Introduction

A performance standard is a statement which can be expressed in qualitative or quantitative terms of the performance required of a system, item of equipment, person or procedure and which is used as the basis for managing a hazard.

High level performance standards may, for example, stipulate that: 'In an explosion event, at least one escape route must be available after the event for all survivors. For a manned platform a TR or safe mustering area must be available to protect those not in the immediate vicinity of an explosion and to survive the event without injury'.

In the UKCS, the frequency with which accidental events, from all causes, will result in loss of TR integrity within the required endurance time will not exceed 10^{-3} per year [14]. The required endurance time is the estimated time for people to travel from their workstations to the TR, then to the primary and secondary means of escape, allowing for the possibility of helping injured colleagues.

To reiterate the regulatory requirement, performance standards may also be referred to as acceptance, screening or performance criteria and SECEs are defined as, any structure, plant, equipment, system (including computer software) or any part of those (a) the failure of which could cause or contribute substantially to a major accident; or (b) a purpose of which is to prevent, or limit the effect of, a major accident [15, 16].

In addition to the high level Performance Standards above it will be necessary to define measurable performance standards for specific key items or systems relating to the systems' functionality, availability and survivability. These are referred to in this document as 'element specific performance standards' used in the evaluation stage of the explosion assessment. These are sometimes referred to as low level performance standards.

Structures can be designed to respond elastically (i.e. in the elastic deflection range) or plastically to explosion loads. In the latter case, structures will be found to have resistance to higher levels of explosion. For design based on a SLB, the structure should not be permanently damaged by an explosion; however, the ultimate acceptance of the topsides structure should be based on the DLB.

For design to resist the DLB, the primary structure should not collapse with escape possible from safe areas after the event. Plastic deformation of the structure is acceptable provided collapse does not occur and barriers remain in place and are able to resist any subsequent fires. The ability of the structure to satisfy these requirements will depend on its ability to respond in a ductile manner and the ability of the barrier connection details to respond without rupture.

7.5.2 Criticality categories for SECEs

It is helpful to consider a hierarchical approach to the identification of SECEs. It is suggested that the number of SECEs (systems, equipment or functions) requiring detailed assessment are classified into three levels of criticality with respect to the explosion hazard. The basis for the performance standard is also given in each instance:

- Criticality 1 – Items whose failure would lead to direct impairment of the TR or EER systems including the associated supporting structure. These items must not fail during the DLB or SLB, ductile response of the support structure is allowed during the DLB.
- Criticality 2 – Items whose failure could lead to major hydrocarbon release and escalation affecting more than one module or compartment. These items must have no functional significance in an explosion event and these items and their supports must respond elastically under the SLB.
- Criticality 3 – Items whose failure in an explosion may result in module wide escalation, with potential for inventories outside the module contributing to a fire due to blowdown and or pipework damage. These items have no functional significance in an explosion event and must not become or generate projectiles.

7.5.3 Design criteria

In explosion resistant design, the prime objective is often energy absorption and not static strength, particularly for the extreme low probability scenarios. However, limiting deformations need to be set in some parts of the structure which may be influenced by plant, equipment and piping. In general, increasing the stiffness of a structure can result in local stiff points that attract high loads and lead to brittle failure modes that may compromise the integrity of the whole system.

Undesirable modes of failure are:

- Those resulting in an overall collapse of the structure.
- Those involving sudden failure such as local buckling.

In addition, there is a requirement that the explosion must be contained, in order to prevent an escalation of the event. Consideration needs to be given to limits of deformation, as determined by the location of pipes and equipment and to the performance of these items. The limits specified for the structural elements should not exceed those required for the supported or adjacent equipment to function adequately.

Design criteria for structural elements that are normally considered are:

- Strength
- Deformation limits
- Local and global ductility
- Rupture
- Global collapse

7.5.3.1 Strength

Where strength governs the design, failure is assumed to occur when the design value of the internal force or moment due to the design action exceeds the design resistance. The design action is determined by setting the partial action factors to 1.0 and adding the explosion actions. The design resistance is determined with the partial resistance factor set to 1.0.

7.5.3.2 Deformation limits

Permanent deformation can be acceptable following an accidental event provided that the following can be demonstrated:

- No part of the structure impinges on critical operational equipment.
- The deformations do not cause collapse of any part of the structure that supports critical equipment, the safe area, evacuation routes or muster stations; a check should be performed to ensure that integrity is maintained if a subsequent fire occurs.
- The deformations do not cause escalation of the event (e.g. by damaging riser integrity or ESDV control).

7.5.3.3 Local and global ductility

Deformation limits for structural elements are normally specified in terms of deflections, often given as a ductility ratio, μ, defined as the ratio of the maximum displacement of the element to the deflection required to cause first yield at the extreme fibres. This is a global deformation parameter, which is commonly used in a SDOF model. A local ductility parameter may also be defined in terms of the support rotation.

For a Class 1 section, Dowrick [17] allows a limiting support rotation of 2 degrees and a ductility factor of 10 (whichever governs) as reasonable estimates for absolute values to ensure safety for personnel and equipment, consistent with maintaining structural integrity in the inelastic range. It should be noted that such levels of ductility would have design implications for members developing plastic hinges to ensure the ductility levels can be achieved. This is normally done by providing lateral restraint to the unbraced compression flange at hinge locations.

Norsok Standard N-004 [7] gives in Annex A the range of allowable ductility values depending on the section classification and the boundary conditions (assuming no axial restraint to the beam). These are reproduced in Table 18.

Consideration of attached fire protection may impose a lower limiting strain or deflection. The displacement of the component must also be limited to prevent impacting SECEs and equipment items.

Table 18: Allowable ductility values, μ

Boundary Conditions	Load	Cross section Category		
		Class 1	Class 2	Class 3
Cantilevered	Concentrated	6	4	2
	Distributed	7	5	2
Pinned	Concentrated	6	4	2
	Distributed	12	8	3
Fixed	Concentrated	6	4	2
	Distributed	4	3	2

7.5.3.4 Rupture

Structural integrity is often assessed using strain limits, which if exceeded would cause rupture. Current guidance on allowable strain values are to set the critical percentage strain limit at 5% at weld locations and 15% in the parent material away from welded details.

These values refer to average local strain values. However, it is important to be aware that strains at this level are quite sensitive to a number of parameters and tests show a significant scatter of strains at fracture. The Norsok Standard [7] highlights a number of factors that influence the strain values such as material toughness, presence of defects, strain rate and presence of strain concentrations. Strains are normally adopted as a failure criterion when using finite element models to judge response. It should be noted that variations in strain are quite common depending on the modelling assumptions used and care in interpreting these values at critical points is required. For more detailed guidance on material models to be used in FEA reference should be made to [18].

7.6 Structural assessment

7.6.1 Introduction

The degree of complexity adopted in establishing the response of the topside requires considerable engineering judgement at an early stage in order to avoid unnecessary delays in the design process. Screening of various options for blast walls or potential behaviour of walls and decks under a number of explosion scenarios requires cost effective, reliable and accessible solutions. In many cases, this may mean that complex NLFEA is unlikely to be an option in the early stages of the design cycle unless planned well in advance. Once the design has matured and the SECEs of the structure have been identified, NLFEA is likely to be required to verify the design.

For retrofit projects, it may be important to obtain the ultimate capacity at an early stage, which may require a more refined analysis at the outset. This will assist in determining the degree of retrofit required although other factors such as shutdown period if hot work is required and space available will also influence the options available. It is also important to bear in mind that simple models may not give a satisfactory design for large overpressures, as many of these tend to rely on bending capacity from a static analysis with some form of load factor to account for the dynamic response.

In order to decide on the level of assessment that is required for various parts of the structure and at different stages of the design, the philosophy for the explosion design load cases and corresponding performance standards need to be established.

A performance standard relating to strength of members is more suitable for the SLB, as this is predominantly a stress based check using static design codes. For the DLB, an ultimate capacity check is required and the yield stress limit will be exceeded; member stress is not appropriate for judging member response. In an assessment against DLB, deformation limits are normally adopted.

The SLB may typically have a peak overpressure in the region of 0.5-0.6 bar. It should not be less than the 0.34 bar [19] as a minimum lateral pressure to be resisted by walls in order to achieve a minimum level of robustness in the connection details.

7.6.2 Strength level blast

Existing design codes (predominantly for static loads), with enhanced factors to allow for the material properties due to strain rate effects and differences between guaranteed minimum yield strength and coupon tests can be used for the SLB design checks. This is likely to involve simple numerical models such as the Biggs SDOF idealization [20] or a static FEA for the primary steelwork. The use of simple models will allow a rapid assessment of the suitability of the layout of the primary steelwork and the screening of a number of pressure-time histories to establish the bounding loading case. Performance standards based on design strength are adopted for assessment against SLB. It is important to be aware of limitations of this approach:

1. Design codes are based on static not dynamic loads. This is particularly important when checking members in compression as buckling is a time dependent phenomenon, which may invalidate some of the static code checks.
2. It is essential to allow for the enhanced reaction forces and moments at connections due to the enhanced yield stresses that may occur.
3. Membrane forces may occur in some elements that may not have been accounted for in some code checks.

7.6.3 Ductility level blast

At this load level, permanent deformations due to yielding are acceptable. For parts of the structure that need to contain the blast, care needs to be taken to ensure that they remain sufficiently functional to prevent an escalation of the event. Some local rupture of structural elements can be tolerated if it can be shown that progressive collapse will not occur.

In some cases, a maximum deflection limit may be specified to avoid compromising supports to vital equipment or pipework, which may lead to an escalation of the event. The adequacy of components is checked against performance criteria based on maximum deformation and strain rather than strength.

The ultimate acceptance based on the DLB should demonstrate that:

- There is no sudden or progressive collapse of the overall topsides structure.
- There is no excessive damage to SECE, e.g. by limiting deflections and acceleration of the structure (avoidance of escalation potential).
- There is no structural damage that significantly affects subsequent fire endurance.

Analysis of this level of deformation inevitably requires the use of more complex analytical tools, such as NLFEA techniques that are capable of modelling large deformation and strain. It is also important to capture the effects of interaction of the structural elements as a system, in order to assess the possibility of a global collapse mechanism occurring. Uncertainties still exist at such large strain values, which are inevitable in many instances, and care needs to be taken when interpreting the results of nonlinear analyses.

7.6.4 Dimensioning explosion loads

Dimensioning explosion loads [21] are of such a magnitude that when they are applied to a simple elastic analysis model, the code check results in members dimensioned to resist the worst credible event or DLB. The definition of the SLB in this guidance may also serve to perform this check for the DLB with the more stringent requirement that the stresses in the primary structure remain below yield.

Joints, panels, barriers and connections still need to be checked against the DLB directly preferably using a nonlinear elastic-plastic analysis.

7.6.5 General remarks on structural response

Yasseri [22] described a useful hierarchy of structural systems in which components that were subjected directly to the blast, such as walls, deck plating including stiffeners and cladding are defined as the secondary system. The primary system is those elements that have blast loads transmitted to them from the secondary system and consists predominantly the primary structure typically consisting of plate girders, beams, columns and trusses.

For the primary system, which is crucial to the survivability of the structure under the extreme load condition, it is necessary to ensure that it remains predominantly elastic. Parts of the structure that are allowed to yield should be detailed for high ductility. This will be mainly the blast walls and plating, which if allowed to deflect, will reduce the loads transmitted to the primary framing. This places emphasis on the connection details, which need to be assessed for large rotations in order to achieve a robust structure.

7.7 Response prediction methods

7.7.1 General

Several techniques of varying complexity are available for predicting the blast response of topsides. These range from simple hand calculations and graphical solutions to more complex 3D analysis capable of modelling geometric and material nonlinearity, tearing of welded connections and contact with other parts of the structure or plant and equipment. However, with all of the models available, a considerable degree of engineering judgment and experience is required in order to convert the real structure into the idealised model.

The general philosophy is to start with the simplest methods (ensuring a conservative approach) and if failure is indicated, proceed to more sophisticated methods of analysis.

The three main levels of analysis are:

1. Screening analysis
2. Strength level analysis
3. Ductility level analysis

The following may enable simplifications to be made in the analysis method:

- Non load bearing elements, typically cladding panels, firewalls, and blast walls may be checked in isolation.
- The stresses in panels and cladding due to blast usually dominate the stresses due to frame movement.
- Panels and some blast wall systems may be conservatively idealized as one-way spans.
- Resistance displacement curves may often be determined statically, dynamic response may then be determined using a modified Biggs method [23, 24].
- Dynamics of simple structures may be represented with knowledge of dominant natural period.
- Biggs method extensions are available for loaded components and generalised boundary conditions [23, 24].

It is preferable to check the primary structure response to the SLB using an elastic frame model as single member assessment does not take into account the transfer of loads between connected loaded surfaces and any co-existent static loads. It is preferable not to include non-structural cladding and plates in the model as their response is mainly in membrane action and their shear strength may be overestimated.

7.7.2 Screening analysis

7.7.2.1 Condition assessment

Screening analysis of an existing installation consists of condition assessment, which may involve a survey followed by design basis checks.

The transfer of conclusions and load characteristics from the analysis of a similar platform is acceptable for this and for Strength Level and Ductility Level analyses.

7.7.2.2 Design basis checks

The purpose of design basis checks is to determine whether the methods used in the design of the installation are acceptable in the context of the fire and explosion events being considered.

If the structure and appurtenances have been checked for safety level or ductility level earthquake loads following API RP 2A [25] (9th edition Section 2.3.6e.2 or later) then the 'strong shock' response to explosions need not be checked.

7.7.2.3 Component checks

Component checks may be employed if the component is non-load bearing in the operational condition or if the component does not form part of the main framing (primary system). Methods of dynamic response assessment such as Biggs method [20] may be used. Where loads from connected structures are present, component check methods may be employed. There are, however, many limitations on the method, which are discussed later in Section 7.7.6.

A major consideration in explosion response is that deflections of the structure must be limited to allow escape. Typically, the deflections into escape ways should be limited to about 150 mm. The allowable deflection into equipment spaces will depend on the clearances to equipment. The deflections of the Primary structure will normally be satisfactory if it passes the normal strength or utilization checks. Blast and firewalls are, however, designed to deflect to exploit the ductility of these items and so deflection checks for these items will be necessary. Buckling checks must also be performed to ensure that the full plastic capacity of a member can develop.

7.7.3 Strength level analysis

The integrity of an offshore structure may be checked using a linear elastic analysis under the SLB. It is conservative not to include the restraint provided by the cladding or barriers in the primary frame computer model. In some circumstances, it is advisable not to include the cladding as plate elements as the shear restraint from these elements will be overestimated in a linear elastic model. This applies particularly if an external explosion load is considered which puts the sidewalls with respect to the pressure into shear. In a dynamic analysis, the masses and their distribution should be included in the model. In checking the primary structure, it is conservative to include the loads from barriers but to ignore their strength contribution.

The response of cladding panels and plates may be analysed in detail separately from the primary structure using FEA assuming the supporting beams are fixed at the main nodes of the structure. The justification is that the stresses in the panel are dominated by local response of the panel out of plane while the stresses induced by the deflection of the main framing are comparatively small. If necessary, this assumption can be checked by application of prescribed displacements to the edge of the panel corresponding to the frame response.

Buckling checks must be performed to ensure that the full plastic capacity of a member can develop. These checks should be made particularly for deck beams loaded by an explosion below the deck as flanges usually in tension may be in compression during the explosion. These checks should ideally be performed using the loads for the DLB and SLB load cases. Deck beams loaded by an explosion below the deck should also be checked for rebound effects.

In a static analysis an equivalent static load, as described in Section 7.3.1.1, will need to be defined for application of explosion loads as a static load case. The permanent loads in the structure need to be combined with a realistic estimate of variable loads to perform a strength level analysis treated as a design load case. Environmental loads need not be included. BS EN ISO 19901-3 [4] recommends that partial load factors for the permanent, variable and explosion loads are set to 1.0. A number of issues must be considered when applying code checks in a strength level analysis (see Section 7.9.3).

7.7.4 Ductility level analysis

For most ductility level analyses, code checking will either not be appropriate or the response simulation software will not contain a code check module within the software. Checking of members will be done explicitly with regard to performance standards, which may take the following forms.

- Strength limit checks (similar to code checks). Failure is defined to occur when the design load or load effects exceed the design strength. This criterion may be applied in the plastic region.
- Deformation limit checks. Permanent deformation may be acceptable so long as safety critical equipment is not impinged upon and collapse is not caused even in the presence of a fire. Mechanisms may be formed momentarily during an explosion.
- Buckling checks. Identify where plastic response may be limited by local buckling.
- Fracture checks. Identify weld and member failures.

Cross sections may be classified as Class 1, 2, 3 or 4 (BS EN 1993-1-1 [26]]). Class 1 and 2 sections will generally reach their full plastic capacity before buckling.

If the structural response software is capable of representing finite displacement effects, plates may be included in the model to represent barriers and loaded surfaces. The inclusion of plates with equivalent thickness to represent mid-point deflection will also help to represent the tension and shear effects from these items.

The restraining effect of cladding can conservatively be omitted from the computer model so long as the loads applied to them are applied to the bounding members according to the area associated with each one. Some packages will not take account of the loss of shear restraint from the cladding, as it is deformed; in this case, it is preferable not to include the cladding as plates in the model.

7.7.4.1 Deformation limits

Deformation limits were discussed in Section 7.5.3.2. Additional Guidance is given in this section.

Class 1 sections may be designed using code checks without supplementary local buckling checks up to first hinge formation. Section 7.2 of FABIG Technical Note 4 [27] gives formulae for checking local buckling of beams working beyond the elastic limit.

In most situations, blast walls are arranged to span from floor to ceiling without direct support from the columns. Isolated columns only receive load from dynamic pressures and could be in tension during an explosion. Allowable ductility ratios based on earthquake design practice are available for I-sections, box sections and circular sections from the literature [28].

Buckling checks must be performed to ensure that the full plastic capacity of a member can develop. These checks should be made particularly for deck beams loaded by an explosion from below the deck as flanges usually in tension may be in compression during the explosion. These checks should be performed using the dimensioning explosion load level.

Table 1 of FABIG Technical Note 4 [27] gives criteria for the prevention of lateral torsional buckling based on slenderness ratios of beams. Large deflection effects such as web crushing and flange curling are dealt with in Section 7.4 of the same FABIG Technical Note.

7.7.4.2 Joint design

The principal ultimate failure mechanism for joints is rupture or brittle fracture unless the joint is stronger than the members that are connected to it. The basic principle is to design connections so that loading or imposed rotation causes ductile deformation in the connected members. This follows general practice in earthquake design. A more detailed appraisal is given in Section 9.4 of the FABIG Technical Note 4 [27].

7.7.5 Single degree of freedom idealisations

The basic analytical model used in many blast design applications is the SDOF system. Much of the guidance developed is based on the Biggs method [20]. Other methods based on an energy balance to obtain iso-damage curves developed by Baker [29] are also adopted and the basis and limitations of these techniques are described in this section.

7.7.5.1 Component response – Biggs method

Components may be analysed in isolation as long as the interaction with the surrounding structure and its applied loads are negligible or are represented in the component model [30].

SDOF methods represent a structural system as a single mass whose motion is resisted by a single linear or nonlinear spring. The magnitude of the mass and the stiffness of the spring are determined such that the displacements in the SDOF model are the same as a characteristic displacement of the real system, usually taken to be mid-span displacement.

The SDOF method is limited to structural systems that can be easily simplified to a single mass and spring. These are systems where the overall response may be represented by a characteristic displacement and the deflected shape is similar to the first or lowest mode of vibration of the system.

The SDOF method can easily be programmed onto a computer, which can calculate the displacements at each time increment. The equations of motion can be modified during the time-stepping process, to allow the modelling of changes in structural behaviour at certain displacements. For example, the change in structural stiffness caused by plastic deformation can be introduced when the yield displacement of a beam has been exceeded, hence modelling the increased plastic displacements. Explicit solutions of the equations of motion do not have to be found, and hence it is relatively simple to use nonlinear force and resistance inputs without significantly increasing the complexity of the program. This is particularly useful in the analysis of blast panels, where the resistance-displacement relationship is complex.

The Biggs method requires two basic inputs, the resistance displacement curve and an idealized pressure time history. Design charts are available [20] for the calculation of the peak response, $x_{\max}$, given the load duration to natural period ratio, t_d/T, and the ratio of peak overpressure load to component ultimate plastic resistance, F_m/R_m. The charts are based on simplified bi-linear resistance behaviour, which is inaccurate for fully or partially fixed members as well as for members where tension effects are significant. This procedure is illustrated in Figure 21.

The mass and stiffness of a structural member must be carefully represented in the SDOF model to ensure that the model displacements accurately represent the displacements of the actual member. The mass and stiffness of the member, as well as the loads applied to it, are modified using transformation factors which are calculated taking into account the deflected shape and the loading and mass distributions [20].

The values of the transformation factors are dependent on the deflected shape of the member under the blast load. If the deflected shape of a member changes as it is loaded (for example if plastic deformation occurs) the transformation factors must be adjusted. Methods of calculation of mass, K_M , and stiffness, K_L, transformation factors for beams and panels are given in the literature [20].

The natural period of the member is given by:

$$T \quad = \quad 2\pi\sqrt{\frac{M_e}{k_e}}$$

where

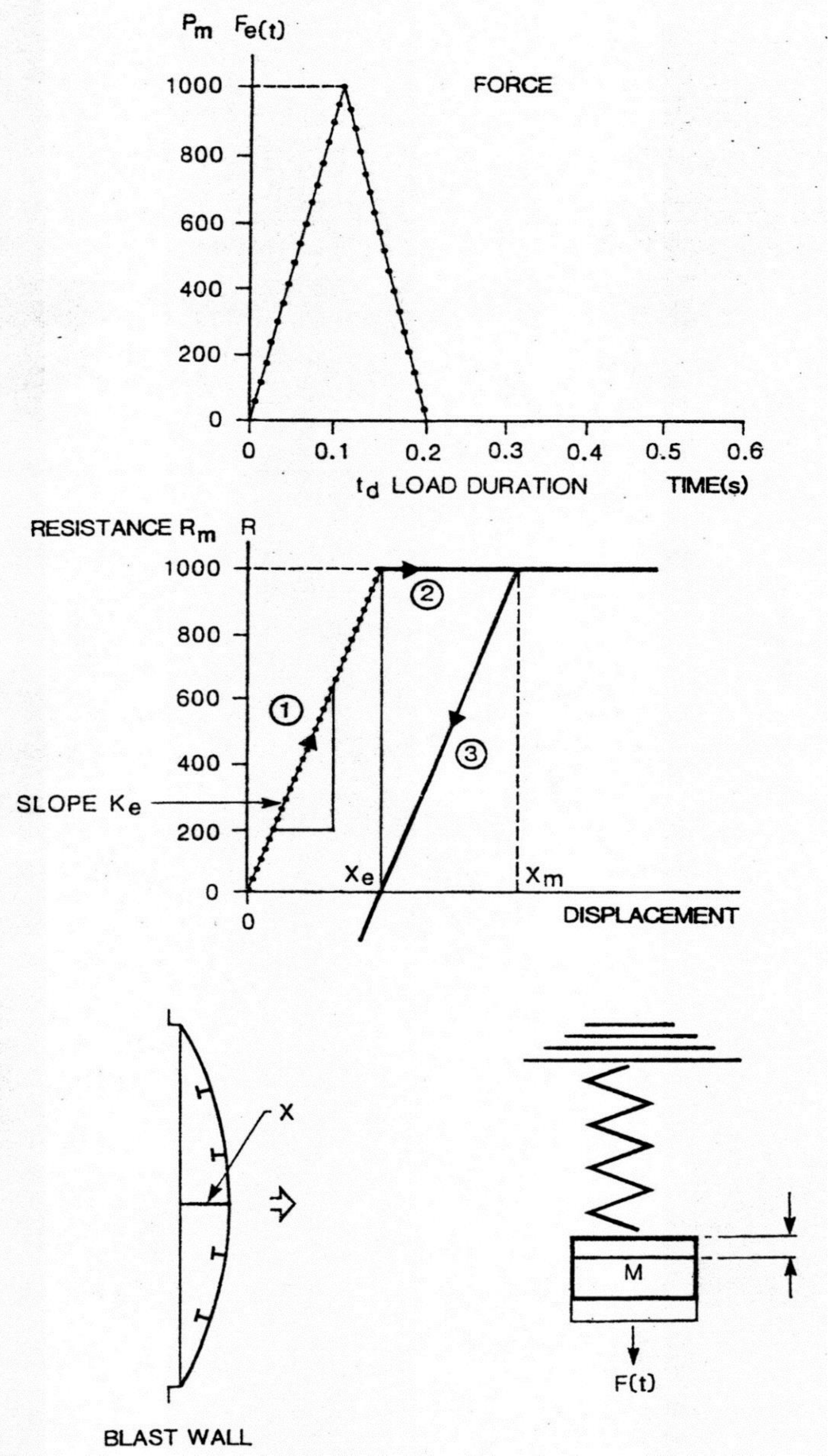
M_e is the actual member mass, M , multiplied by mass transformation factor, K_M

k_e is the actual member stiffness, k , multiplied by stiffness/load transformation factor, K_L

A typical idealized resistance-displacement curve for a simply supported beam is shown in Figure 21 [30]. Under increasing uniform loading, the member deflects elastically up to its yield displacement, x_e . Further loading results in no increase in the resistance of the member, i.e. it is assumed that the member is deforming purely plastically. If the displacement reduces after plastic deformation then it is assumed that the resistance of the member returns to the pre-plastic (or elastic) form on a line parallel to the line representing the initial elastic deflection.

Member damping is not usually modelled in this analysis, and hence the member oscillates freely after the blast load has been removed. In practice, damping is not important as it is generally small for structural members oscillating in air and, in any case, it is the maximum displacement rather than subsequent oscillations that is important.

Figure 21: Biggs single degree of freedom model



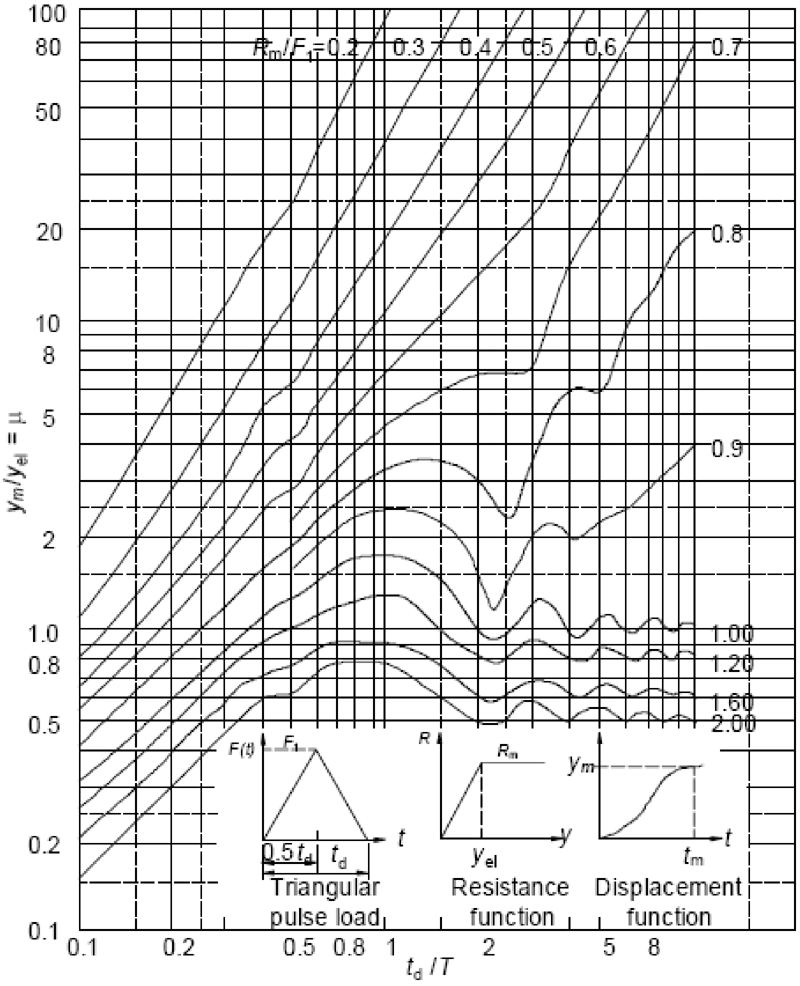
7.7.5.2 Representation of fixity conditions

The degree of rotational and axial fixity at the ends of a structural member affects its elastic stiffness and hence its natural period. The bi-linear resistance-displacement relationship used in the Biggs design charts is only accurate for simply supported members, where the member reacts either purely elastically or purely plastically. For partially or fully fixed members, elastic/plastic behaviour occurs before the member reaches its ultimate plastic resistance.

The Biggs charts use an approximation of member stiffness to give a bi-linear resistance curve for all fixity conditions. The stiffness used in the Biggs method is determined such that the area under the 'actual' and 'idealized' curve are equal, and hence the energy or work done to reach a given deflection is the same for the two curves.

A range of values of F_m/R_m and t_d/T were used to generate the sets of curves shown in the Biggs design charts. Figure 22 is a typical example for a simply supported member under a triangular load with a rise time equal to half the load duration. Similar charts for differing rise times of triangular loading are given in the literature [20].

Figure 22: Biggs design chart – overpressure rise time equals half load duration



The chart in Figure 22 enables the peak response of the member to be calculated. The vertical axis is provides a measure of the ductility, which is the number of multiples of the yield displacement the member will reach under the loading.

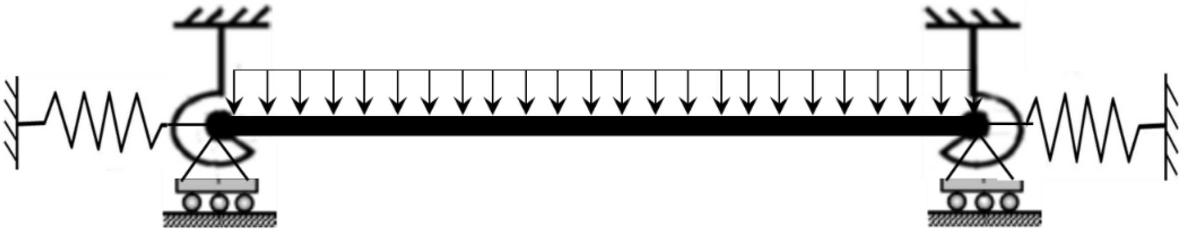
To use this chart:

- Determine the peak resistance (R_m), effective stiffness and yield displacement (X_e) for the member.
- Determine the effective peak force (F_m) from the peak force (F_{peak}) and the load factor K_l ($F_m = K_l \times F_{peak}$).
- Calculate the equivalent mass of the member (M_e).
- Determine the natural period of the member from the effective mass and stiffness.
- Choose the nearest curve corresponding to the ratio of F_m/R_m.
- Read off the ductility for the peak response corresponding to the t_d/T for the member.
- Calculate the peak response from the ductility indicated on the vertical axis.

The reaction loads at the ends of the member may also be estimated using this method although the accuracy may be doubtful as detailed strain information is not represented in the model. These formulae are not accurate for two-way spanning panels but are reasonable for the assessment of one-way spanning panels or beams.

Biggs method was extended [23] to incorporate the effects of support axial and rotational flexibility, differing moment capacities at the two supports and the effect of catenary action giving generalised boundary conditions as shown in Figure 23. Catenary action can have a significant effect on the response when large displacements of the member occur in the presence of axial restraint at the supports.

Figure 23: Generalised boundary conditions for SDOF analysis [23]



In this extended method, it is assumed that the two supports can provide a degree of rotational restraint to the beam such that the plastic mechanism in the bending range consists of three plastic hinges. Accordingly, the response prior to the formation of a bending plastic mechanism, typically consists of a three segment piecewise linear curve, as illustrated in Figure 24. The cases of one or both supports providing no rotational restraint are subsumed in the developed model by setting the corresponding support rotational stiffnesses to zero; for such cases, a fully plastic response, associated with a plastic mechanism, is attained without plastic hinges at the corresponding supports.

After the formation of a plastic mechanism, the static bending response becomes perfectly plastic until a mid-span displacement of r_p^t. Subsequently, a first catenary stage is initiated in which the axial force varies as a quadratic function with displacement, leading to a cubic variation in the resistance, R. Finally, when the axial force reaches the overall plastic axial limit, F_p^m, (limited by the lesser of the axial capacity of either of the two supports or the member itself) a second catenary stage is initiated with a linear variation of *R*. The three stages of plastic bending and catenary response are illustrated in Figure 25. Two alternative models are considered for the plastic response, which differ in the extent of the plastic bending stage and in the modelling of the first catenary stage: i) a simplified piecewise linear model and ii) a detailed nonlinear model.

Reference [23] gives an extensive set of tables for the calculation of the transformation factors for use in SDOF analysis. The steps for implementing a numerical explicit time integration in a SDOF analysis are also set out in detail and a number of examples given. The method was further extended in [24] to account for strain rate sensitivity.

Figure 24: Stages of bending response through hinge formation

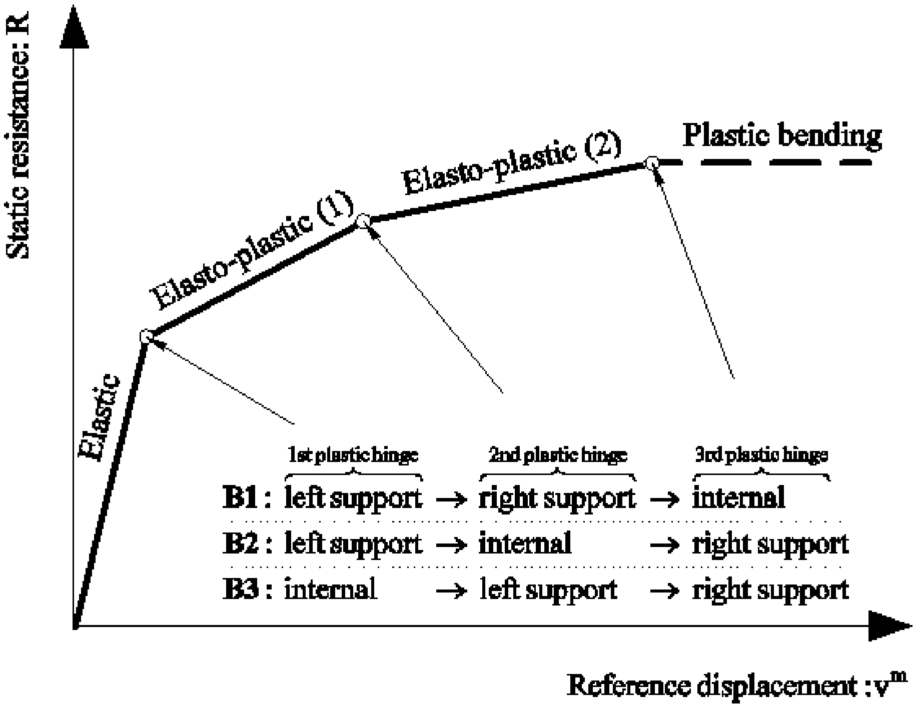
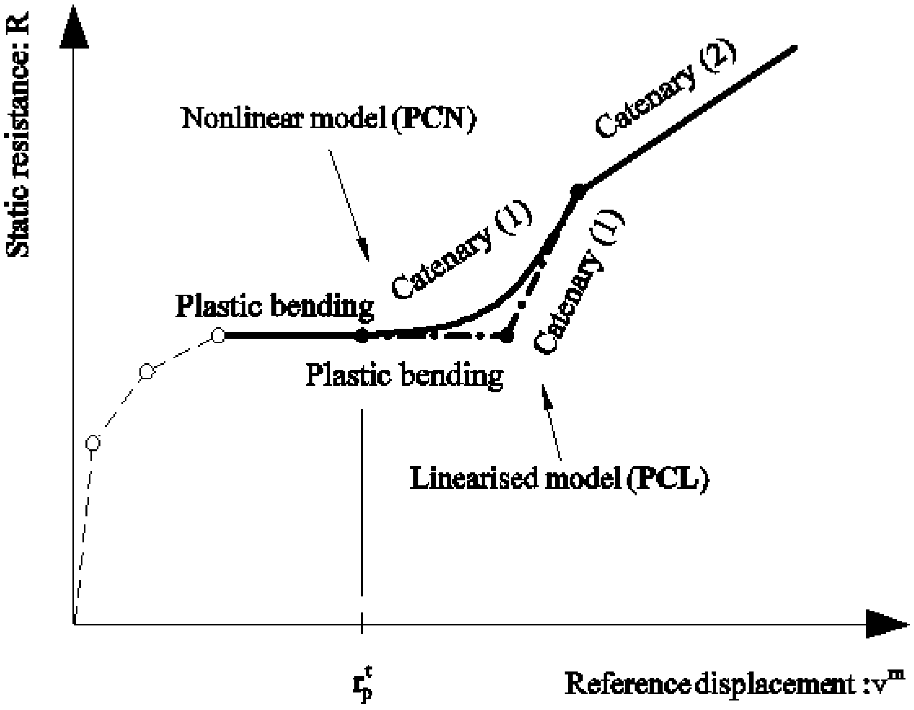


Figure 25: Stages of plastic bending and catenary response



7.7.5.3 Out of plane equipment loads

Attached equipment alters the natural period of the member by increasing the mass, which must be accelerated during blast loading. A one degree of freedom idealization may be adopted to check the response of deck sections if a Screening Analysis is being performed.

The effect of static out of plane loads is to cause an initial deflection of the member. The deflection will be positive in the case of a floor beam subjected to blast loading from above, and will be negative in the case of a ceiling beam subjected to blast loading from below. The initial deflection due to the out of plane loading effectively changes the position of the origin on the resistance/displacement graph.

The resistance function may be modified to take into account equipment loads. The same Biggs chart may be used to estimate peak response so long as the natural period and resistance function are modified to represent attached masses. This has been implemented in online software [31] along with the above extensions to Biggs method.

7.7.5.4 The effect of in-plane loads

Whilst purpose designed blast walls will have no static loads applied to them, there is often a need to assess the capacity of module walls and columns with in-plane loads present.

In-plane (i.e. axial) loads have 4 effects on the response of structural members:

1. Axial loads reduce the plastic moment capacity of a section. Under the dead and live loads normally applied to structural members, the reduction in plastic moment capacity is small.
2. Axial loads change the stiffness and hence the natural period of a member. The stiffness of a member will reduce to zero at the Euler buckling load.
3. As an axially loaded member deflects under blast loading an additional moment will be generated by the axial load about the original centre line of the member. This 'P-Δ' effect is modelled by converting the moment caused by the axial load into a lateral resistance, which is then subtracted from the original beam resistance.
4. An axial load may be applied eccentrically to the member, creating an initial central deflection. The reduction of blast resistance due to eccentric axial loading is modelled by reducing the resistance of the member at the initial deflection.

The dominant effect on response is the P-Δ effect. As blast walls are usually arranged to span from floor to ceiling, the direct explosion loads on columns are small and these effects may be ignored in a screening analysis.

7.7.5.5 Barrier and cladding response

Blast walls are usually designed to deform plastically and act predominantly in bending to minimize the reactions on the primary structural members of the platform. A great deal of effort is usually expended in designing the edge connections of the blast wall so that the reaction loads are transmitted to the supports without damage to the supporting steelwork. Because of the inertia of the wall, it is possible to design these connections such that the transmitted shear forces and moments are much less than the peak overpressure force on the wall. Purpose-built blast walls are usually free standing, spanning from floor to ceiling and are not an integral part of the supporting structure.

The capacity of a blast or firewall with stiffened plate construction may be estimated for Screening Analysis purposes using the methodology in [32]. The possible failure modes of the wall may include panel, stiffener and whole wall failure. Each mode corresponds to a different plastic hinge, or yield line pattern. Local and torsional buckling of stiffeners and wall plate may also occur before plastic hinge formation. The failure mode corresponding to the lowest ultimate resistance is the critical failure mode of the wall.

The calculated resistance will also depend critically on the edge support conditions assumed which may in turn depend on the form of loading. High pressure loading on adjacent panels may give rise to clamped edge conditions between panels even though the panels would not otherwise merit this approach. Tension and membrane effects often indicate an increased resistance but the restraint from the surrounding structure through inertia or stiffness may not be sufficient for these effects to be fully mobilized. The effect of membrane action can be checked using the modified Biggs method [23, 24].

Penetrations such as piping and cable runs should be arranged to pass through the wall at the top or bottom of the wall to limit deflections and induced strains in the wall. The penetration should be fire and gas proof. The penetrated section of the wall should be designed to have the same stiffness and strength as those parts of the wall where no penetrations exist. The dynamics of the wall and penetrations may need to be checked if large mass items are attached to the wall.

7.7.5.6 Rebound

Rebound occurs when the load has subsided and the stored elastic energy in the wall is released. This may be taken into account by assuming a reverse load or suction at a level of 1/3 of the original overpressure with the same duration.

Biggs method may also be used to determine the rebound response if a suction phase is included in the load time history. Other authors have developed a rebound DAF that may be used to calculate rebound response [33].

7.7.6 Limitations of Biggs method

The advantage of Biggs method is that it is simple and easy to apply once the structure is idealised into a SDOF system. However, the basic Biggs model represents simple bi-linear structural behaviour assumptions that may limit its applicability for design of modern lightweight structures. It is important to bear in mind that in the past, guidance that was developed for blast resistance design was based on using structural strength, weight and standoff from the explosion source to control response of land based structures.

Some of the limitations of the Biggs method that need to be considered include the following:

1. It is not easy to convert anything other than the simplest structures into equivalent spring mass models. A great deal of engineering judgement is required in determining meaningful models and interpreting the solutions. For example, modules are normally framed for lifting and to give redundant load paths, making the overall structure of the module difficult to describe as a one degree of freedom system.
2. The deformation of structural components such as walls and decks is highly dependent on the degree of restraint provided by the primary steelwork. Although some membrane action can be incorporated into the model, it is difficult to accurately model the stiffness of the boundary. Whilst Biggs did not address this, the refinements implemented to the Biggs method [23] incorporate the necessary generality to deal with boundary restraints.
3. Ductility factors used are normally for idealised simple beam models. These may not be appropriate for the actual structure where different patterns of yielding could give the same overall inelastic peak deflection but the local ductilities may be significantly different.
4. The Biggs method implicitly assumes that the deflected shape under blast loading is the same as the static deflected shape. Many multi-degree of freedom systems or systems with complex mass distributions do not respond in this way. This also applies to some stiffened plate blast walls.
5. The loads obtained from a CFD model may indicate that they vary significantly in both space and time requiring some conservative idealisation to simplify them so they can be used with the SDOF model.
6. The method relies on the fact that the mass can be lumped, but deck type structures are likely to have significant mass components from plant and equipment. This spatial variation in the mass may well invalidate the assumed shape function and give non-conservative results. Biggs [20] does address this problem but refinements of this method have considered the effect of distributed and point loads on beams [31]. If the rebound is more important, which may well

be the case if the ceiling of a module supporting plant is being considered, then care needs to be taken [33].

7. The prediction of rupture is very unreliable as there is no detailed representation of the strain distribution within the structure. High ductility deflections are not well represented by the flat portion of the resistance displacement curve representing plastic response.

Although some of the limitations above seem severe, the technique has been successfully used in design situations, particularly where the resistance function has been accurately determined. FABIG Technical Note 4 [33] shows an example of a stiffened plate whose resistance function was determined via a static NLFEA and combined with the spring mass model. The deflection time histories compared well with an explicit NLFEA up to pressures of the order of 3 bar. Beyond this, the model was unable to give accurate deflection values. This was thought to be due to the spread of plasticity that results in a change of the shape function used in formulating the spring mass idealization.

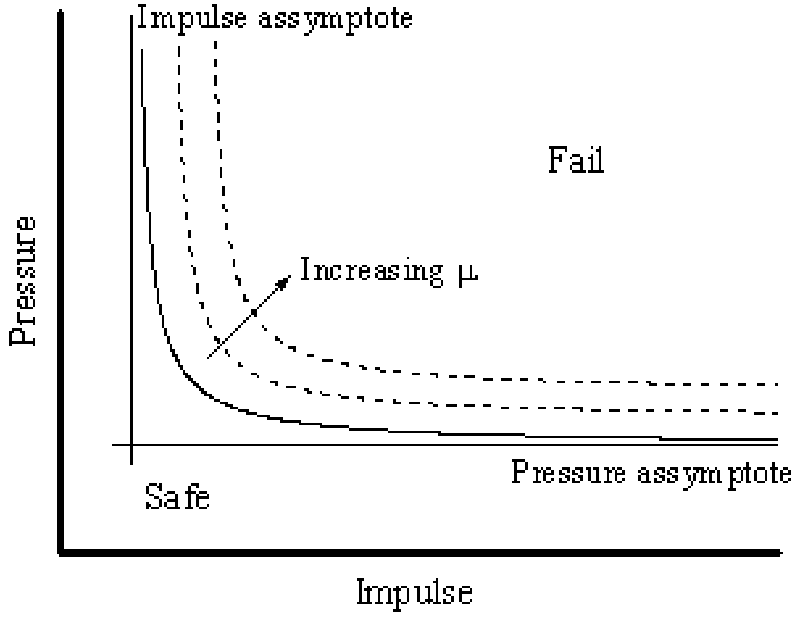
7.7.7 Pressure impulse diagrams

Rapid assessments of maximum response are very useful in a preliminary structural design, particularly where there are a large number of load cases to screen. The Biggs model described how transformation factors can be developed using an energy balance to convert the structural element into a spring-mass model. The same concept is adopted in developing pressure impulse diagrams, described in detail by Baker [29]. An example of a pressure impulse diagram is provided in Figure 26.

For an impulsive load, the maximum strain energy may be equated with the initial kinetic energy imparted to a structure or structural element by a short duration pulse. Similarly, for quasi-static loading the maximum strain energy may be equated with the maximum external work for a long duration pulse is determined.

A suitable shape function is required to describe the deformation under the loading and both elastic and plastic behaviour can be accounted for. The resulting expressions for the two loading regimes are then rearranged such that a non-dimensional plot of pressure against impulse can be constructed. A number of curves are normally plotted for varying levels of damage that may be defined in terms of the ductility parameter, μ. This allows rapid assessment of the damage or vulnerability to a number of different loading conditions. The method is capable of representing membrane action in elements such as plate components. The method can also be applied to certain systems that are not easy to define using a SDOF model. It can be taken a step further by constructing pressure impulse diagrams for a number of different elements such as beams, plates and columns for a series of damage levels. The damage calculated for each component is then combined in a weighted manner, depending on the vulnerability of each component, to define overall module damage.

Figure 26: Pressure impulse diagram



7.8 Nonlinear finite element analysis

7.8.1 General

The NLFEA is, potentially, a very accurate tool, and often the only tool available, for predicting response of complex structures under extreme loading. Impediments to the wider use of this powerful modelling tool are continuously being overcome by advances in computer technology. However, it is still very much a specialist tool because of its general-purpose characteristics and the tendency to inherently overestimate the resistance of structures if used incorrectly. Undertaking analysis of complex structures using NLFEA requires a detailed understanding of the potential failure modes of the structure and the contribution of coexisting operating actions to component utilization. Overall modelling accuracy can be checked by comparing results with those of the same case in a linear-elastic analysis.

The most severe limitation of nonlinear finite element modelling is the dependence on low level performance standards, which in general means that a significant amount of time may need to be invested in setting up the models and interpreting the results. However, in most cases the reward is a more cost efficient design. Detailed guidance on the use of structural response NLFEA is given in [18].

7.8.2 Choice of tools

A suitable NLFEA tool should as a minimum have the capability to account for nonlinear and rate dependent material behaviour, geometric nonlinearities, large displacements, local and global instability in the structural response. Geometric nonlinearities include opening and closing of gaps, material ruptures and contact between separate components.

7.8.3 Construction of the finite element model

One of the first choices the analyst is faced with when defining a numerical model of a given physical problem is where to set the outer boundaries of the model. Another key decision is the type, or combination of types, of elements to be employed. In general, beam elements are employed for the analysis of complete modules, shell elements for the analysis of decks, walls and structural components, and solid elements for the analysis of connection details.

The numerical model should include sufficient parts of the supporting structure to ensure that end-restraints are modelled realistically. This is especially the case when determining the membrane forces developing in structural components undergoing large displacements. The membrane forces have the effect of increasing the resistance of a structural member by delaying the onset of buckling, and can also significantly alter the reaction forces. In this context, it should be noted that when membrane forces develop in one part of the structure they are usually counterbalanced by compressive forces in other parts. These compressive forces may have an adverse effect on the stability of the structure.

Rather than opting for a high overall level of detailing in the modelling of structural assemblies it is often possible, without loss of accuracy, to employ the output of one model to drive a displacement-controlled analysis of a sub-model. An example of sub-modelling is the assessment of the containment pressure of a blast wall. Typically, the stiffened or corrugated plate is represented by shell elements. A sub-model of solid elements is employed in order to assess whether or not the ultimate resistance of the welded connections has been exceeded.

The converse of displacement driven sub-modelling is to use the results from a few lower level analyses, such as those carried out to find the deformation capacity of connections and welds, to define member performance standards applicable to the higher level analysis.

A further complication often encountered in the NLFEA is the presence of mathematical singularities, which occur where elements meet at sharp corners. The analyst needs to be aware of this numerical phenomenon, and may have to investigate this in further detail by employing refined models.

In order not to overestimate the ductile capability of members, it is very important that the FEA takes due account of all the potential buckling modes. Consequently, the mesh density needs not only to be fine enough to achieve convergence, but also needs to be sufficiently fine to represent all the dominant local buckling modes. This can be obtained by dividing each structural element susceptible to buckling into at least 6-8 elements across the width (e.g. of a plate between edge supports or of the flange of beam). Furthermore, the analyst may have to introduce imperfections or destabilising loads in order to trigger numerical buckling.

For large assemblies it is not practical to make the mesh fine enough to capture all the buckling modes. Hence, the individual structural components need to be checked until the analyst is satisfied that all potential failure modes have been accounted for.

It is also considered to be good practice to keep the aspect ratio of 2D and 3D elements as close to unity as possible, and only to gradually change the sizes of the elements in the mesh. Post processing tools can play an important role when investigating whether the meshing is adequately fine.

For most models, it is necessary to specify appropriate multiaxial constitutive equations for the material. For steel materials, Von Mises yield criterion used in conjunction with an isotropic hardening rule and an associated flow can be employed in situations where the critical response is reached during the positive phase of the blast loading. In situations where plastic strain reversal is significant, a kinematic hardening model is preferred.

The spatial and temporal distribution of strain rates and their adverse influence on the reaction forces need always to be considered when performing a plastic analysis.

When analysing structural components it is usually assumed that the pressure time history is uniformly distributed over the surface. However, when carrying out a global structural analysis the ability to describe non-uniform loading, which also varies in time, is often required. Blast loading should at all times remain normal to the surface of components undergoing large displacements.

The analyst should recognise and possibly need to include the fact that the structure is in a state of static equilibrium at the time of blast loading. Ignoring the service loads when calculating the blast resistance will not necessarily be conservative. Permanent loads associated with heavy equipment are best modelled by transferring the load through discrete fixing points, which can be mutually constrained. Other service loads are included using a smeared approach.

7.8.4 Solution techniques in NLFEA

Two fundamentally different solution techniques can be adopted based on implicit and explicit time integration algorithms.

In general, the explicit method is best suited for the analysis of blast-loaded structures, where the transient responses are to be measured in tens of milliseconds, and large plastic deformations develop. The explicit algorithm requires relatively little computational effort at each time step since no formal matrix factorisation is necessary. Another advantage of explicit solvers is that they have an inherent ability to initiate most of the local buckling modes. However, unlike implicit solution schemes, which are unconditionally stable for large time steps, the explicit scheme is stable only if the time step size is sufficiently small.

Implicit methods on the other hand are essentially static codes running in the time domain, and will as such require much more memory and disk space. The degree of nonlinearity of the problem makes the larger time steps permitted in the implicit codes of little practical value.

7.9 Response of the primary structure

An important factor that mitigates the effects of an explosion on a large structure or structural component is the fact that the peak pressure does not act simultaneously on all parts of the structures. As the blast wave travels over the structure, different parts will be loaded at different times with the result that the average global pressure may be significantly reduced. This can be illustrated by a numerical example.

Consider a blast wave of 50 ms duration travelling at the speed of sound (C_0 = 340 m s^{-1} in ambient conditions) along a wall or across a deck. The blast wavelength in this case is $L_d = t_d \times C_0$ or 17 m. A typical bracing member or panel 8 m long will hence be subjected to a peak averaged pressure of 0.75 of the peak. A module wall that is 35 m long will be subjected to a peak averaged pressure of 0.25 of the peak value.

In situations where a large deck is considered these conclusions may only apply locally as the pressure loading pattern may be circular or irregular in shape. Furthermore, the local effects of the peak pressure may still need to be considered.

7.9.1 Global received loads

Global loads on primary members are dependent on the capacities and dynamic properties of the connected panels. Often the loads transmitted into the primary framing will be reduced by panel capacities and the delay in load transmission due to delayed panel response. The panel peak response may well occur long after the blast load has subsided and if a suction phase is present then the panel response itself may be reduced.

Often the direction of the loading on the primary framing may be changed locally due to panel membrane effects. These membrane loads may be balanced globally if panels of similar dimensions are attached to either side of the columns.

7.9.2 Plasticity and dynamic effects

The Biggs chart shown in Figure 22 may be used to estimate the benefit to member capacity from plastic deformation and dynamic effects (within the constraints that the chart is applicable to the structure and loading considered).

If a member has a t_d/T ratio of 0.2 for example, and a ductility of unity is required (elastic response) then the static resistance to load ratio is about 0.6 and the member will resist (dynamically) a load of 1/0.6 = 1.6666 times the member resistance. For elastic response the DAF for this case is 0.6.

If a ductility of 10 is allowed then the resistance to load ratio is about 0.15 and the member will resist a load of 6.66 times the member resistance. Hence a four-fold increase (6.66/1.66) in capacity when the ductility ratio is increased from 1 to 10.

Values of ductility above 4 may be reached for structures with long natural periods (large frame structures or compliant structures). The allowed ductility will depend on the applicable performance standards. A DLB performance standard could well allow a ductility level of 10 for decks and beams.

7.9.3 Modified code checks

The design of the topside components of an offshore hydrocarbon production facility is traditionally carried out using codes of practice based on conventional static design, where the elements are required to remain elastic under normal service load conditions. This involves comparing maximum stress levels in the members with capacities derived from the code of practice.

As an initial screening process, this approach can be used before further checks and analyses are carried out, particularly if the overpressures are not high (say, less than 0.5-0.6 bar). The checks can be carried out with some relaxation on the design yield strength, which is normally based on a guaranteed minimum value and an allowance for the increase in the yield strength due to strain rate effects. Allowing for strain rate effects will extend the elastic range and this needs to be considered in the buckling checks. In addition, the forces at the connections will increase, and connection adequacy will need to be reconsidered.

Checking the primary structure against the SLB (in the case where the load is 1/3 of the DLB) will often size the members for the DLB. Experience suggests that the Primary structure will not experience the full overpressure loading as the loading acts first on secondary members, barriers, cladding and plate [6, 21]. Unity or utilization checks to the appropriate standard (e.g. EN1993-1-1 or AISC) may be reinterpreted to reflect the reserves of strength in the structure.

When compared with a Ductility Level Analysis this approach often results in a less efficient and heavier structure. These methods will not be suitable for the analysis of a situation where a fire has preceded the explosion unless allowance is made for material weakening and geometric imperfections, and permanent deformations resulting from the fire.

Blast resistant structures and their supports are designed to respond in a ductile way to explosion loading mainly in bending. The shear behaviour of structures at their supports and in the joints of the primary frame will also affect the utilization factors derived in the code checks. The safety factors implicit in the code checks will be different from those associated with bending. Shear strains at supports should generally be limited to the elastic limit.

Additionally, for a dynamic situation these shear forces will be quite different from the values obtained by static analysis as a result of the inertia forces acting on the structure. The benefits of this effect are exploited in blast wall design, as the support or reaction loads may be less than the applied overpressure load. Plastic deformation of a blast wall also has the effect of limiting the reaction loads on the supports. The shear forces could be higher for a loading duration near the natural period of the member. Checks should be made where this is likely using a DAF based on the ratio of load duration to natural period.

In an allowable stress design, code checks may be reinterpreted to take account of the following inherent reserves of strength:

- The explosion event is an accidental event and hence the stress may be allowed to approach yield. A factor of 1/0.66666 (1.5) is then appropriate on the allowable utilization. Alternatively, the yield stress may be enhanced by the same factor to allow for nonlinear relationships for some aspects of utilization factor calculation.
- The material strain rate effect will generally give an increase in yield stress of the order of 20%. This value is used in the nuclear industry [34] and may be higher locally, in particular in high strain regions of a blast panel. A factor of 1.2 may be applied to the acceptable utilization or to the yield stress.
- Strain hardening will occur around regions of local plasticity. Where it is appropriate (for tension members, Class 1 sections in compression and/or bending), allowance may be made for this by taking the design yield strength as the ultimate tensile strength divided by 1.25 (Section 3.5.8 of the IGNs [2]).
- The occurrence of plastic hinges may be taken into account by factoring the acceptable utilization factor by the ratio of the plastic, Z_x, to elastic section modulus, S_x. This factor is

generally greater than 1.12 and will be in the range 1.1 to 1.5. The member must be able to sustain the formation of a plastic hinge before buckling, i.e. be in tension or be a Class 1 section.

As discussed above shear checks should also be made using the correct dynamic reaction loads with strains being limited to elastic limits.

Taking into account all the factors above gives a possible acceptable utilization factor of 1.5 × 1.20 × 1.25 × 1.12 = 2.5 for a tension member. Usually the benefit of both strain hardening and strain rate yield strength enhancement is not taken into account. Hence, ignoring the benefit of strain hardening, the recommended acceptable utilization factor is 1.5 × 1.20 × 1.12 = 2.0 for primary members acting in bending and/or compression under explosion loading so long as the member does not buckle where local buckling is not acceptable. Discussions of buckling checks for members working beyond the elastic limit can be found in the literature [27, 28]. It is stated by Kato [28] that Class 2 and Class 3 sections may be designed using code checks without supplementary local buckling analysis up to the formation of the first hinge.

A limit state approach may also be used with the equivalent elastic load level for the DLB derived from consideration of the differing partial safety factors suitable for the ultimate limit state and serviceability limit state. Further discussions of these topics can be found in [6, 21].

7.9.4 Global response considerations

Finite element analyses may well be used for a full wall or deck, but modelling a complete module, integrated deck, an assembly of modules or complete topsides of a fixed or floating facility requires another order of magnitude of effort, computing power and cost. Accurate modelling of both geometry and mass distribution is required, in order to achieve a realistic dynamic response.

Many different blast simulations may be required in order to generate a realistic envelope of responses for specific details. A balance has to be struck between the extent of the model and the level of detail in order to be cost effective. Inclusion of small details such as penetrations and stiffeners may not influence the global response and thus becomes irrelevant for a global model. Application of point masses at deck level at primary model nodes may also be sufficient to achieve an acceptable accuracy for vertical dynamic response. Elevated masses may be required for significant items of equipment or vessels where rotational effects may be important and local horizontal loads are present.

Major pipework may need to be modelled if it could influence the dynamic and explosion response of the structure, particularly if it has been detailed in such a way as to provide an explosion resistance load path between decks via pipe supports.

Elastic global models may be conservatively used to determine accelerations of primary elements remote from an explosion, on complete modules such as the Living Quarters or for lifeboat and muster areas. Dynamic amplification for such areas can thus be determined for use in local analysis.

Rigid boundaries for panel assessments are not necessarily conservative if the operating condition deformations are not considered. The sensitivity of the explosion capacity to dead and operating load should be addressed, as should the sensitivity to residual fabrication deformations and stresses. Welding residual stresses should also be considered in connection assessment, especially if key components are limited in capacity by the 5% weld strain limit. The weld geometry needs to be addressed for ultimate capacity calculations, especially in fillet-welded details, as a considerable portion of the total capacity of a connection may be absorbed by secondary loads generated by eccentric load paths.

In 'brownfield' reassessment of explosion capacities, deflection criteria may become critical, especially in circumstances where blast panels come into contact with primary framing braces at loadings beyond the design overpressure. This can be common with linear elastic designs, say, to 600 mbar design overpressures, which are revised to 2 bar overpressures following updated CFD modelling. Care should be taken over the capacity of the framing braces, in that they may not have the capacity to carry the transferred loads from the blast wall in combination with the dead loads from the deck above. Destabilisation of the brace could result in potential toppling of any supported tall structures. In these circumstances, the total dynamic loading on the brace needs to be considered, including the explosion loading on connected decks.

An advantage of global models is the ability to visualise modes of mitigation, which may otherwise not be apparent when focussing on individual components or panels. Tying long span decks together to limit the deflection under heave is a means of limiting damage to equipment and pipework, which would otherwise suffer consequentially from large displacements. The loading required for design can be extracted from a global dynamic analysis that incorporates the ties affecting the dynamics of the deck girders. Care must be taken in detailing, however, in order to prevent operating loads being transmitted into the ties.

7.10 Response of equipment, pipework and vessels

7.10.1 General

In areas of a production facility with an explosion risk, the following load conditions or actions need to be addressed for pipework, vessels, equipment, cabling and their supports, plus other miscellaneous items, such as scaffolding and loose items:

- Dynamic pressure loads (comprising drag and inertia components)
- Differential pressure
- Differential movement
- Strong vibration
- Missile generation and impact

Areas remote from, or physically separated from, the regions with the direct explosion risk should also be assessed for these actions if there is a potential consequence to personnel safety or integrity of safety critical systems, including personnel escape provision. Dynamic pressure loads are, potentially, the most severe design loadings on equipment, vessels, pipework and cable trays.

Differential movements may generate significant loads where adjacent supports respond differently to an explosion. For instance, a vessel will be supported from the deck of a module, but pipework connected to the vessel may be supported from the roof of the module. In an explosion, the deck and roof will deflect in opposite directions, imparting loads on the vessel nozzle, potentially triggering a further hydrocarbon release, which could be catastrophic in terms of escalation of the event. Similar effects could be seen with pipework connections to equipment and with pipe branches, or where supports are positioned either side of stiff deck elements leading to support rotations in opposing directions.

Loose items subjected to blast wind, components that break free from their supports in the explosion, or fragments of equipment or vessels generated by the break-up of those items all have the potential to become missiles that can then impact other equipment, vessels, pipework or critical electrical and control systems. The potential for loose items to become missiles needs to be controlled by good working practices; the potential for items to break free and become missiles, or for vessels and pipework to break apart and become missiles, needs to be controlled by design.

The dynamic response of the vessel or equipment on its support steelwork is fundamental to the reactions that are generated. Very stiff supports will generate high reactions; flexible supports will generate lower reactions; supports that are too flexible may not be tolerable for operational reasons, or for retaining continued integrity following an explosion event. Too much allowable movement may also contribute to vibration modes of failure for connecting pipework.

7.10.2 Response of equipment and vessels to explosion loading

For large diameter vessels, there should be consideration of the near-uniform pressure loading, as well as differential pressure and blast wind. Process vessels need to be assessed for the vessel stability when subjected to explosion overpressures. In many cases, the blast overpressure will have negligible effect if the internal operating pressures are of a greater magnitude. However, the external overpressure could be a significant cause for concern if ignition was to follow blowdown, as process vessels are not normally designed to withstand net external pressure loads in excess of 1 bar.

In most circumstances, the critical explosion loading effect on a vessel will be a lateral loading or overturning effect on the supports. For 'brownfield' reassessment cases, this may be well above the design loading magnitude, as the design explosion loading would have been on a par with the accelerations allowed for in the transportation or earthquake scenarios. Under higher explosion loadings, this may no longer be the case and modification of the vessel supports may be required. As discussed above, support strengthening may lead to an increase in the support reaction, so modifications should be carefully assessed. Often a linear elastic design may be demonstrated to have adequate ultimate capacity if reassessed using nonlinear dynamic techniques, with full use of material certificates.

The vessel should be considered rigid in order to develop support reactions, but the uncoupling of loads onto the deck steelwork needs to be considered in conjunction with the deck loading from the explosion. A simple SDOF solution may not be appropriate, whereas NLFEA would be.

For equipment supported on anti-vibration mounts (AVMs), this could mean retention of lateral stops or shear keys, which would otherwise be removed after the transport and installation phase. The deck plating or under-deck bracing must be assessed for adequate resistance to the lateral explosion loads. Tall equipment (relative to the support footprint) must be assessed for the possibility of toppling under explosion loading. A similar approach to that for large vessels discussed above can be taken for the support reactions and the response of the under-deck steelwork.

Attachments to equipment must be assessed for the possibility of differential movement between the equipment supports and the attachment supports. This is particularly important with small bore pipework, e.g. fuel gas lines and instrument pipework. Long spans for small bore pipework should be avoided in order to limit vibration problems caused by flow turbulence, but normal operating vibration considerations are likely to govern.

7.10.3 Response of pipework to explosion loading

Pipework supports are generally designed to withstand gravity loads and allow thermal expansion of the line. Flowlines are designed to tolerate a specified rotation or lateral movement of a well conductor or pump caisson. In some instances, the lateral loading caused by slugging forces must also be allowed for. However, the lateral loading generated by blast wind loads must also be accounted for, in order to prevent excessive mid-span deflections or displacement of the pipe from its supports, which in turn leads to a rupture of the line or potential flange leakage. Comprehensive guidance on the design of pipework against fires and explosions is given in FABIG Technical Note 8 [35].

Differential movement between adjacent supports, whether at a pipe branch, transition from deck to roof support or between modules must be accounted for when considering explosion loading. It may well be prudent to design the first support from a pipe branch as a structural fuse, in order to prevent a line from breaching under explosion loading. Pipe runs on FPSOs are designed to accommodate significant movement due to vessel flexing. Safety critical pipework on fixed structures in regions of significant potential movement due to explosion loading should have the same considerations. Explosion loading on pipework will be significantly increased by turbulence and congestion. Reduced piperack support reactions may be achieved by the use of baffles or slipstreaming aids, in order to present a single large rounded face to an advancing shock wave.

Explosion loading assessments should not be restricted solely to oil and gas lines, but must also include deluge pipework, as these are SECEs for potential fires following explosions.

Given the problems associated with developing a time-domain loading for a complete pipe run, an appropriate test for robustness would be to consider each pipe span as simply supported and use a SDOF approach. The tension capacity of the piping dominates the response and a pure plastic resistance may be assumed for the pipe span with the mid-point deflection being the relevant response variable. Plastic hinges soon occur at each end of the pipe when the pipe may be assumed to be simply supported.

Consideration of the equilibrium of a length of pipe between supports as a catenary yields a time history of the tension in the pipe, T_p, and the extreme deflection of the mid-point enables the plastic strain at each end to be estimated using methods given in the previous section. An average plastic strain limit of 5% and a peak local strain limit of 10% may be used to determine failure of the pipe. These failure criteria apply to all reasonable pipe sizes and are insensitive to pipe diameter. If the pipe supports are attached to beams of similar section properties then the differential movement of the deck under an explosion should not be a problem.

7.10.4 Strong vibration

Strong vibrations are caused by shock or displacement waves transmitted through the decks and walls as a consequence of the explosion. These need to be allowed for in the design of sensitive equipment, piping, electrical connections and instrument panels. Strong vibrations could lead to the toppling of tall items of equipment or instrument cabinets, damage to valve actuators or large bending forces on long unsupported spans for pipework or cable trays. It should be recognised that vibrations could be either vertical or lateral, depending upon the support arrangement of the item relative to the deck or wall transmitting the shock wave.

If the structure and SECE's appurtenances have been checked for a safety level or ductility level earthquake loads following API RP 2A 9th edition (Section 2.3.6e.2) [25] or a later version, then the 'strong shock' response to explosions need not be checked.

Once the force is calculated, it may be applied to a dynamic global platform structural model. The displacements and accelerations at points on the topsides may then be calculated. These accelerations are potentially damaging to essential safety systems such as:

- EER systems
- The TR and its supporting structure
- Emergency lighting systems
- Emergency power supply and battery systems
- P.A., telecommunication systems and navigation aids
- Fire water systems
- ESD systems

One further consequence of shocks of this kind is that pipe runs between modules may be stressed due to relative displacements between modules. This would be particularly important in SECEs, e.g. for the fire water main.

If the accommodation module or TR is supported on AVMs the acceleration may be further amplified due to resonance by the low frequency components of the shock.

For a fixed platform, the integrity of the substructure should be checked against out of balance explosion loads. It is likely that the explosion loads will have a duration in the range of 50 to 100 ms whereas the substructure will have a natural period of sway in the range of 2 to 4 seconds. For elastic response of the jacket, a dynamic amplification (or reduction) factor may be calculated from the ratio of load duration, t_d, to the natural period, T. A reduced equivalent static load may then be derived which can be applied to the fixed platform computer model. Typical dynamic reduction factors of the order of 0.05 may apply in which case problems with the substructure are unlikely. This load case may then be eliminated from consideration, on the basis that the equivalent static loads on the substructure are smaller than those induced by waves and currents. Floating, tethered and moored installations are unlikely to suffer serious response to this form of loading because the natural period in the horizontal direction is much longer than the load duration.

Awareness of strong vibration is essential in the design and protection of safety systems used for:

- ESD
- emergency power
- communications
- fire protection
- deluge pipework
- fire and gas detection
- heating, ventilation and air-conditioning (HVAC)
- EER

Systems which some may consider not safety critical also need to be assessed for the effects of strong vibrations: e.g. grating on escape routes, stair towers, module stools. Such systems are fundamental to the safe evacuation of personnel from the facility and strong vibration or blast wind loading may be the governing design load case.

Control and instrument cabinets in utilities areas, which are protected from the direct influence of explosion loading, should be assessed for the risk of toppling by strong vibrations. Battery racks should have a retaining bar across the front of each shelf. Even bookshelves in critical areas such as the Control Room should be assessed for the risk of displaced objects, which may fall and damage control panels or cause injury to key personnel.

Massive objects with sensitive connections to adjacent machinery should be particularly addressed. Isolation or shut down valve actuators, rotating machinery such as pumps, turbines and compressors, HVAC dampers and lifeboat mountings should be reviewed for the consequences of shock or strong vibration loading.

Walkdown is now a commonly used tool to perform a qualitative assessment of the risk of damage from strong vibration [36].

8 Fire and explosion hazard management in design

8.1 Introduction

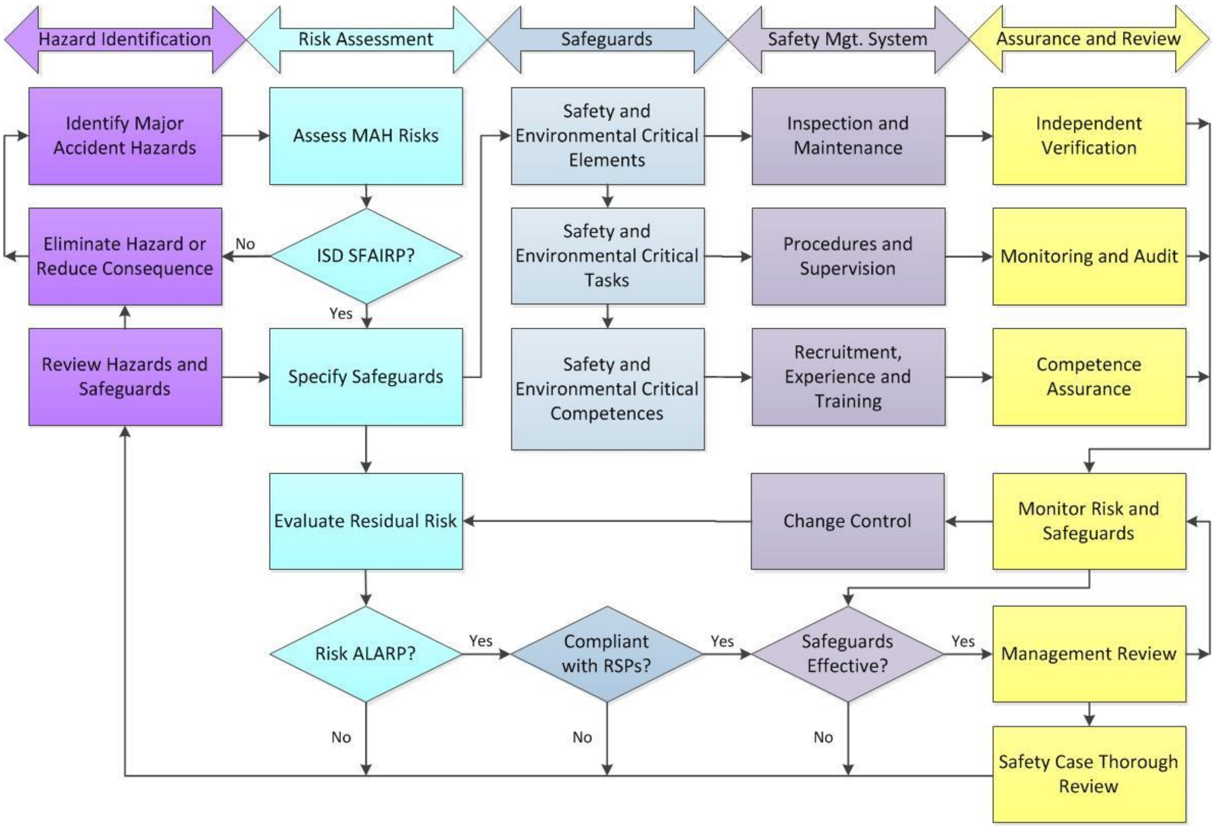
Earlier chapters of this guidance outlined the hazard management activities to be undertaken at various stages in the lifecycle of an offshore installation from selection of the design concept, through construction and operations, to decommissioning. This chapter provides guidance on how these should be applied within the delivery of oil and gas development projects. The objective of this section is to provide additional, qualitative and pragmatic guidance on designing to reduce fire and explosion risks at each step of the design process and is primarily intended for discipline engineers and project managers.

Figure 27 shows an overall framework for the management of MAHs presented as a flowchart that relates the principal elements of:

- Hazard identification
- Risk assessment
- Barriers and safeguards
- SMS
- Assurance and review

This framework can be applied to the full range of hazards and is relevant to all aspects of fire and explosion hazard management. The discussion below is structured accordingly, noting that most elements of the hazard management framework apply to all lifecycle stages, though their relative importance may vary between stages.

Figure 27: Framework for the management of major accident hazards



8.2 Project hazard and risk management strategy

Despite the complexity of fire and explosion phenomena, experience shows that, with the application of a rigorous hazard and risk management process throughout the project lifecycle, offshore fire and explosion risks can be kept to tolerable levels. This is achieved by designing with MAH issues in mind throughout every stage of a design project.

The overall objective of the project hazard and risk management strategy can be summarised by the following steps:

- Minimise hazards through the application of ISD.
- Identify the remaining threats.
- Identify the vulnerable targets.
- Determine the escalation potential if the target is impaired.
- Assess the likelihood and duration of impact on each of the targets.
- Specify barriers to protect targets from threats.
- Specify performance standards for each barrier.
- Review the residual risk and determine if the risk is tolerable and ALARP.
- Iterate the risk assessment and barrier provision until risks are ALARP.

Early within the programme of any project, it is important to establish a SEMS to provide a working process; adherence to which will ensure that the risks to people will be reduced to ALARP and that any potentially adverse impacts on the environment are managed consistent with the best available technique (BAT) principle. In the establishment of the plan there should be a preference given to hazard elimination and prevention ahead of control and mitigation. This leads to a hierarchy of risk reduction measures (in decreasing order of preference):

- Elimination and minimisation of hazards by design (i.e. ISD).
- Prevention (reduction of likelihood).
- Detection and control (limitation of scale, intensity and duration).
- Mitigation of consequences (protection from effects).
- EER arrangements.

It is likely that during the execution of a project a combination of these measures will be used to manage any given hazard. Throughout the project lifecycle decisions need to be made many of which will have a direct impact on the risk to people, the environment or the asset, from concept selection through to decisions on construction methodology.

It is general practice within the offshore industry (for all but the most minor projects) to have specific Health, Safety and Environment Plans drafted at the earliest practicable stage. This Health, Safety and Environment Plan defines how safety and environmental aspects of the project will be managed and the typical contents will include:

- An introduction to, and outline of, the project.
- Relevant legislation and applicable procedures and standards to be applied to the project.
- A specific project HSE policy statement with reference to that of the organisations involved.
- A summary of the safety criteria and targets set for the management of safety and environmental hazards in design.
- Details of the roles and responsibilities of those persons named in the safety organisational structure, including all levels within the project.
- Details of how the technical competency of the operational and design personnel is guaranteed.
- Details of the design integrity reviews on the project needed to ensure the appropriate level of safety and environmental hazard management.
- A schedule of safety engineering deliverables (i.e. documentation to be produced).
- The procedure for the control of quality regarding bought-in items, services and sub-contracts.
- Details of an audit plan to assure the delivery of the above activities.

The overall framework for the management of fire and explosion hazards put in place from early concept design will need to be reviewed and further developed through each project phase.

European Standard EN ISO 13702 [1] provides more guidance on layout, control systems, protection and mitigation systems, EER arrangements and inspection, testing and maintenance issues in relation to the management of fire and explosion hazards.

NORSOK Standard S001 [2] and its annexes, also provides information on the requirements for layout, structural and process design safety, fire and explosion protection arrangements and communication systems.

8.3 Project phases

The main factors affecting fire and explosion hazards (and their management) throughout the installation lifecycle are summarised in Section 2.12; this section will cover in more detail the overall fire and explosion hazard management design intent and the necessary project design integrity steps for each of the defined project phases.

8.3.1 Concept selection

This section provides design considerations that can be used when selecting various conceptual designs. Guidance is provided for reducing the potential causes, likelihood and consequences of fires and explosions.

During the concept selection phase there will be only very basic well information, production flow rates, vessel inventories, utility requirements and layout data available such that only high-level comparisons can be made. However, it is important that consideration is given to the MAH implications of each of the options identified for development and that this is recognised as a key decision criterion for the final concept selection. An initial hazard review and a simple evaluation of which concept offers the greatest inherent safety with respect to fire and explosion risk should be undertaken and recorded. It is also important to identify and record key areas of uncertainty in the HSE design, as these may have implications for the concept selection process and further should be revisited in later stages.

For greenfield developments (and for brownfield projects where it is clear that the development could have a significant impact on assets risk profile), a formal ISD review should be considered at this stage.

The discipline of recording the basis for the concept selection forces project teams to ensure that the uncertainties and risks associated with each option are considered and that the option decision is made taking these into account whilst balancing the feasibility and practicality of all options.

Some key objectives to consider at concept selection phase with respect to the location of wells, risers and process equipment are:

- Minimise explosion overpressure potential and frequency of occurrence of explosion events.
- Minimise equipment and potential leak sources.
- Reducing complexity.
- Minimise exposure of personnel to hazards.
- Minimising the potential for ignition, including location of ignition sources.
- Minimise escalation potential from fire and explosion events.
- Minimise vulnerability and maximising separation/ segregation of EER systems (including TR) from fire and explosion hazards.
- Minimise exposure of pipeline and risers to routine crane, boat and drilling rig operations.

- Minimise the exposure of critical structures to fire and explosion risks.
- Optimise crane locations, laydown areas and lifting routes to avoid lifts over live equipment or risers, etc.
- Separation of air intakes from potential gas clouds, including the effects of prevailing wind in terms of spread of impact (dispersion of gas or smoke).
- Identify proposed location of future risers, for example, gas lift risers can provide a considerable hazard in later years of operation as the reservoir pressure declines.
- Minimise the flammable and toxic inventories to reduce the duration of release and fire scenarios.
- Maximise structural redundancy to avoid progressive collapse risk.
- Maximise the use of open module design to facilitate better dispersion and dilution of released gas or vapours and provide less containment for explosion overpressure generation.
- Consider the full range of fire hazards, for example, sea surface fires external flaming effects and associated fire sources (e.g. shuttle tanker fires during offloading from FPSOs).

The outcome of the option assessment should be fully recorded in a form that will support the future demonstration that risks have been reduced to ALARP.

Once the design concept is selected, and a basic layout proposed, a multi-discipline layout review should be undertaken. Optimising the layout with regard to fire and explosion hazard potential can minimise the likelihood of release, ignition, and the subsequent impact on exposed equipment, critical systems or personnel.

The layout review should be a multi-discipline activity, as a minimum, addressing the topics and associated considerations listed in Table 19 below. Given that no two installations are alike, there will be many variations on the list of issues to be covered. If such layout issues are not addressed until late in the design process, improvements will be far more difficult and costly to implement.

The table below highlights key considerations to be assessed during the development of the layout in the concept selection phase. The objective is to explore whether the locations of key items that contribute to an ISD can be improved without incurring disproportionate cost.

Table 19: Topsides layout considerations during concept selection phase

Item	Fire and Explosion Considerations
Wells	• Location and segregation for all anticipated well operations (including drilling and workover) and maintenance during field life. • Location, accessibility and vulnerability of automatic and manual isolation valves in fire situations. • Location of artificial lift arrangements, inventories (including down hole gas lift inventories) and isolation.

Item	Fire and Explosion Considerations
Risers/Pipelines	• Riser and riser isolation valve locations – vulnerability to fire attack. • Risers and Pipelines as source of release and potential for escalation. • Riser vulnerability to passing and attendant vessel collision especially during cranes operations. • Future risers, e.g. gas lift risers or other proposed tie-ins.
Process and piping	• Location of major inventories. • Location of relief, blowdown and flare and/or vent lines. • Location of fuel-gas piping and potential for fires/explosions outside main process locations (especially turbine enclosures). • Exposure of personnel and equipment (including piping, instrumentation and SECEs) in closed or open module designs needs due consideration.
Layout	• Separation/segregation of process, drilling, utilities and accommodation. • Separation of key processing equipment, gas compression and separation vessels to reduce the escalation risk. • Layout to maximise natural ventilation and to minimise confinement and congestion.
Structural	• Location of tall structures or structural supports vulnerable to fire attack with severe consequences. • Impact of degree of confinement on explosion overpressures.
Ignition potential	• Location of all non-certified equipment with respect to releases and associated gas plumes, e.g. cranes and generator or motor enclosures.
Egress, escape and evacuation routes	• For potential fire scenarios: • Consider egress routes, checking for trap points or need for protected muster point alternative to TR. • Consider location of escape routes to sea. • Consider time to escalation versus time to muster, appraise and evacuate. • Consider impairment of TEMPSC loading area and helideck access routes.
TR and alternate protected muster points	• Location of air supply ducts. • Vulnerability to heat/smoke. • Vulnerability of TR supports to fire scenarios.
Communications	• Location and vulnerability of any critical communications hardware.

Item	Fire and Explosion Considerations
UPS	• Location and vulnerability to fire.
Fire protection	• Location of firewalls and PFP. • Vulnerability of fire pumps and ring main to damage in fire scenarios. • Vulnerability of deluge piping inside module and supply lines. Location of backup supply lines. • Discharge location for oil and firewater drained to sea in fire incident.
Subsea layout	• Position of pipeline routes to minimise damage potential. • Position of subsea isolation to minimise inventory loss.
FPSO	• Time for escalation of process events to vessel threatening events. • Diversity of escape routes for all fire scenarios (especially process/storage scenarios). • Vulnerability of hull to internal and external process fire scenarios.

8.3.2 Front end engineering design

This section describes the activities and considerations that should be undertaken in FEED with regards to management of risks arising from fire and explosion hazards. At the start of the FEED stage, the basic process design parameters are set down and the key plant items and protection systems are identified and sized. The MAH management activities that should be completed in FEED include:

- Update and undertake more thorough hazard identification (e.g. HAZID, ENVID, etc.).
- Undertake initial characterisation of the hazards, their causes, severity, consequence and potential for escalation.
- Use the developed hazard and consequence knowledge to optimise an ISD and consider the use of a multi-discipline ISD review.
- Undertake a fire and explosion risk assessment and determine the nominal explosion loading.
- Develop the key philosophies, including; process control, emergency shutdown/blowdown, fire and gas detection, material selection, blast design, PFP, active fire protection (AFP) and hazardous area classification.
- Develop the layout and clarify the fire areas and location of firewalls with respect to plant and the TR.
- Designate primary escape routes including stairways, escape to sea locations, and muster/embarkation areas.
- Compile SECE register and set initial performance standards requirements for each system.
- Undertake FEED stage HAZOP and safety integrity level (SIL) determination via layers of protection analysis (LOPA) or risk graph analysis.

- Prepare initial safety requirement specifications (SRS) for all identified safety instrumented functions (SIF).
- Initiate functional safety assessment (FSA) in accordance with IEC61511 [3].

Effective change management is key, especially at this stage of a project, to ensure changes do not undermine the basis of design. At this stage of the design process, fire and explosion management input can still have a major impact on the overall risk levels for personnel and TR impairment.

8.3.3 Detailed design

This section describes the design activities that are undertaken in the detailed design phase with regards to the management of risks arising from fire and explosion hazards. The section also describes design considerations that should be reviewed during detailed design. The overall objective of detailed design with respect to fire and explosion risk management is to ensure that the required prevention, control and mitigation systems are incorporated into the design through the completion of the following activities:

- Ensure that the design meets the requirements of the philosophies established in FEED.
- Ensure ISD opportunities are implemented in the design; or ruled out as not reasonably practicable with suitable justification.
- Undertake the final HAZOP to confirm the safe operation, operability and maintenance of the facility.
- Complete final confirmation of the SIL for all SIFs, typically in detailed design via LOPA.
- Verify that SIL targets are achieved in the SIS design.
- Finalise SRS for all SIFs and conclude FSA in accordance with IEC6511 [3].
- Undertake specific risk assessment as required in line with the guidance on risk related decision making [4] to demonstrate risks have been reduced to ALARP.
- Finalise QRA.
- Finalise SECE register, performance standards, inspection and testing regimes and operational procedures [5].
- Engage with the verifier to establish or make changes to the asset verification scheme [6].
- Prepare the initial safety case or proposed modifications to the existing safety case [6].

8.4 Inherently safer design

The principles of ISD are covered in Section 2.5 including ISD measures commonly applicable to fire and explosion hazards; this section will focus on the application of ISD within the design process [7].

ISD principles should be applied from concept, through detailed design and equipment selection, to the planning of construction activities, and subsequent operations. The aim of ISD is the elimination of hazards, including hazards to the environment, and the minimisation of potential harm where complete elimination of the hazard is not feasible. Adherence to this aim also results in the elimination and/or substantial reduction of the need for engineered safeguards and/or procedural controls. Hazard elimination, or reduction, should be accomplished by means that are inherent to the engineered and planned provisions; and as such are permanent and inseparable from them.

To provide a framework within which an engineering team can identify potential ISD opportunities it is necessary to establish ISD goals, example goals are presented in Section 2.5. ISD goals point the way to those considerations that require particular attention from a safety perspective and provide a framework for the identification of ISD opportunities.

An ISD register should be set up early in each project. Thereafter, there should be progressive population of it, especially at formal multi-disciplinary ISD review events.

In the concept and FEED project phases, an ISD review should be performed after the HAZID and ENVID reviews (note for reasons of timing it is neither necessary nor desirable for a HAZOP or SIL review to have taken place). It is also preferable that an ISD review is performed for detailed design; however, this is dependent upon the nature and complexity of the project and the overall ISD strategy adopted.

The review should be a multi-discipline event chaired by someone familiar with facilitating formal integrity reviews and will generally proceed in the following steps:

- Review the objectives and scope of the project.
- Review the known hazards associated with the project.
- Agree the ISD goals to be achieved.
- Identify ISD opportunities that address each agreed ISD goal in turn.
- Review the ISD opportunities to categorise their feasibility.

The project should then track identified opportunities to a conclusion demonstrating that they have either been incorporated in the design or ruled out as not reasonably practicable with an appropriate justification. ISD features that are implemented should be recorded in a manner that enable their consideration in future developments and modifications to prevent them from being compromised or overlooked.

8.5 Hydrocarbon containment design

The loss of containment of a flammable material is a necessary precursor to the occurrence of a fire or explosion. Hydrocarbon releases are not only potential precursors to major accidents but also a key performance indicator of asset integrity management on oil and gas installations.

Preventing hydrocarbon releases through reducing leak paths and enhancing asset integrity is a primary goal of the HSE and asset operators; and a significant impact on the likelihood of future releases can be achieved in design.

The strategy for engineering design to contribute to a reduction in hydrocarbon releases will include the adoption of related ISD measures and will address the following key objectives:

- Minimise the number of hydrocarbon leak paths.
- Utilise technology developments that reduce potential leak paths.
- Minimise the use of, and maximise the integrity of, connections, seals and flexible hoses.
- Minimise corrosion risk through use of appropriate materials suitable for the lifetime of the asset.
- Maximise the simplicity of process installations.
- Eradicate potential failures from vibration, stress and erosion.
- Manage vendors to include best practice engineering design within vendor packages.
- Ensure the competence of all personnel tasked with the completion of hydrocarbon containing joints [8].
- Reduce human error potential through the application of human factors engineering (HFE), including ergonomic design and accessibility.

8.5.1 Safety engineering

Safety engineering should ensure that there is a defined process to apply the principles of ISD to minimise the potential for hydrocarbon release and that this is applied throughout the project to arrive at a design that has reduced the risks arising from hydrocarbon release to ALARP.

HFE focuses on the application of human factors knowledge to the design and construction aspects of technical systems. The objective here is to ensure systems are designed in a way that minimises the potential for risks from human error [11].

In particular, tasks associated with maintenance, start-up and shutdown where human error could give rise to a hydrocarbon release should be identified and reviewed as safety critical tasks, with particular consideration of access to and visibility of equipment, field instrumentation and valves.

8.5.2 Material selection

Material selection plays a fundamental role in hydrocarbon containment through management of the risks of corrosion and erosion throughout the life of field. It is important to understand the key threats (both internal and external corrosion and erosion) including:

- Sour service (CO2 and O2)
- Chloride stress corrosion cracking
- Sulphide stress corrosion cracking
- Hydrogen cracking
- Microbial induced corrosion
- Corrosion under insulation
- Management of erosion threats including late life sand production

Further good practice is provided in the Energy Institute/OGUK document, Guidance for Corrosion Management in Oil and Gas Production and Processing [9]; this sets out general principles, engineering guidance and requirements for improving corrosion management practices in oil and gas production and processing.

8.5.3 Process design

Of particular significance is the opportunity to apply the principles of ISD and hydrocarbon release reduction at the earliest stages of engineering design, thereby maximising their potential positive impact. This may include challenging the project scope itself (e.g. the redundancy philosophy may double or treble potential leak paths in certain areas).

The process design should aim to minimise hydrocarbon release potential and specifically the following:

- Review of instrument requirements, e.g. eliminating unnecessary transmitters by providing dual functionality.
- Minimisation of flange connections jointly with piping.
- Minimise the use of, and maximising the integrity of, small bore pipework for hydrocarbon containing lines.
- Consider specifying non-intrusive instrumentation where practicable.
- Consideration of fluid/gas transport velocities, e.g. to minimise flow induced vibration and erosion.

8.5.4 Instrument design

Use of identified best practice designs for instrument arrangements can reduce leak paths; specifically the instrument design should consider the following:

- Use of mono-flanges and flange adaptors.
- Minimisation of leak paths in process instrument hook-up design.
- Avoidance of the use of threaded connections where possible.
- Consider the use of specialised third party vendors to achieve a reduction in leak paths and provide the project with the most up to date technologies.

Several specialist vendors offer a service to examine project instrument hook-up diagrams and advise if improvements can be made to reduce leak paths. This service can also be carried out within packages that contain instrument tubing.

Small bore tubing connections are widely used in instrument designs and can introduce a significant risk of hydrocarbon release. Where this cannot be eliminated, the use of appropriate design practices for instrument installations is essential and checks should be conducted to ensure the instrument tubing has been installed correctly [10].

The potential hydrocarbon release risks with small bore instrument installations are:

- Tubing failure due to excessive stresses at piping-instrument interface.
- Tubing failure due to corrosion, internal and external (pitting/pin-holing).
- Tubing failure due to vibration induced fatigue.
- Fitting failure due to inadequate installation practices or competence.
- Over stressed flexible hoses.

Other potential hydrocarbon release risks for instruments are:

- Failures of thermowell pockets, potentially from flow induced vibration.
- Gland packing wear or failure on control valves.
- Failure of seals in insertion probes.

The instrument design should consider the selection and standardisation of component suppliers across the whole project scope, including specification of ratings, materials and sizes to ensure consistency and integrity.

8.5.5 Piping design

Use of identified best practice piping design can reduce leak paths and enhance ISD. Piping specifications and design should aim to minimise hydrocarbon release potential as follows:

- Where practicable avoid the use of small bore pipework for hydrocarbon containing lines.
- Maximise welding and minimise bolted joints and leak paths in piping design (needs to be balanced with the risk of hot work in brownfield projects).
- Ensure correct type of flange connectors have been specified to suit the service and design conditions.
- Consider alternative butt-welded mechanical connectors (e.g. hub connectors, SPO compact flanges) designed in accordance with the relevant ASME codes.
- Minimise the use of hoses on hydrocarbon duty, (where hoses are used, ensure an appropriate risk assessment is undertaken).
- Ensure lines identified as being subject to flow-induced or acoustic-induced vibration have suitable components and supports.

8.6 Hydrocarbon release management and mitigation

8.6.1 Fire and gas detection systems

Early detection of hydrocarbon loss of containment events is crucial. Detection should always trigger limitation of the leak by rapid automatic inventory isolation and should simultaneously alert personnel to the danger.

Fire and gas detection systems monitor and provide early warning of fires and flammable or toxic gas releases on the installation. The detectors are required to detect the presence of fire or gas as rapidly as possible. They provide information on the location of the gas cloud or fire and then raise an appropriate level of emergency alarm to the operating teams and initiate executive actions where required. The alarms should also indicate the location of the event and whether the event is confirmed by other detectors.

The goals for the fire and gas detection system are to:

- Detect: monitor for potentially hazardous releases or accumulations and fires.
- Alarm: initiate alarms to alert personnel to take appropriate response.
- Protect: initiate signals that drive effective actions, whether manual or automatic, to reduce escalation potential and/or minimise loss.

These goals should be achieved by:

- Detecting hydrocarbon gas releases and accumulations at an early stage before they become potentially dangerous.
- Detecting fire at an early stage before it becomes potentially dangerous.
- Providing local, manual facilities to enable personnel to raise an alarm in response to a fire, hydrocarbon release or other emergency.
- Providing measures to minimise the extent, duration and potential for harm or probability that an initial event will escalate to involve other hydrocarbon inventories.
- Providing measures to limit the effects or escalation of a hazardous consequence.
- Reacting to contain, extinguish and remove the hazard; and to minimise the impact, escalation, hazard to personnel and the environment.
- Providing measures to minimise smoke from spreading to other areas and escape routes.
- Providing audible and visual alarm information to alert the operator to the hazard; its location and development/spread; and to enable the operator to make a valid assessment. This can include the requirement to monitor the situation remotely following abandonment.
- Providing audible and visual alarm information to site personnel, to alert personnel and to direct personnel to evacuate in a safe manner.

Most installations have hundreds of sensitive detectors in place. In order to reduce the likelihood of spurious shutdowns and unnecessary platform alerts, most installations have a two-tier alert system. Typically, under this system, a single low-gas-level alarm or fire detection alarm alerts staff in the control room to a potential problem, which is immediately investigated but no shutdown or general alarm is initiated. One single detector response is more likely to be a false alarm than a real gas release or incident. If a second alarm in the same area then occurs or if a high-gas-level alarm goes off, then this is indicative of a real release rather than a false alarm. The fire and gas system voting interprets 2 or more low-level or 1 or more high-level alarms as a ‘confirmed’ gas release or fire. This automatically initiates platform alarms and shutdowns as appropriate.

The aim of the detection systems should be considered carefully; it is important that they detect the events postulated for the installation and act as a coherent component of an overall fire and explosion hazard management strategy.

8.6.2 Detection of hydrocarbon leaks and accumulations

The key objective of the gas detection system is to detect leaks and accumulations of flammable gas as early as is practical such that steps can be taken to limit the size of the release and reduce the likelihood of ignition by inventory isolation and blowdown, and/or isolation of non-ATEX [12] rated equipment. Early warning also allows for timely personnel evacuation and emergency response. It is worth noting that there has to be a leak sizable enough for the gas detection systems to be activated before they are effective and, as such, they are a “mitigation” safe guard. It is not realistic to provide detection systems that can identify leaks of any size.

Generally, flammable gas detectors and leak detection should be located throughout the process areas and locations such as:

- Hydrocarbon process areas.
- Non-hazardous area HVAC air intakes, ventilation air intakes of equipment enclosures.
- Any enclosed/semi-enclosed space where gas may accumulate.

8.6.3 Fire detection

The key objective of a fire and/or smoke detection system is to detect an incipient fire situation early enough to limit the damage to equipment, limit the potential for escalation; by isolating fuel supplies, removing energy sources and activating extinguishing systems. Early warning also allows for timely personnel evacuation and emergency response.

- Hydrocarbon process areas.
- Non-hydrocarbon areas where there are other fire risks.
- HVAC air intakes.
- Machinery enclosures.

8.6.4 Safety integrity level of fire and gas detection systems

It is becoming standard industry practice to set a capability rating for the components of a fire and gas detection system of SIL 2 in accordance with IEC 61508 [13]; and as such the system architecture is designed to meet redundancy and hardware fault tolerance targets. Further guidance on the functional safety lifecycle approach for gas detection systems is provided in IEC 60079-29-03 [14].

It is important to understand that the number of sensing points and their appropriate location, their redundancy, the management of regular maintenance, specifically response checking or calibration, and other gas detection specific features are all likely to have a far greater effect on the integrity of the overall system than the SIL capability of any of the individual functional units [15].

Fire and gas detection systems do not prevent a hazardous situation; but rather in combination with other systems, minimise the consequences and reduce the potential for further escalation. As such the application of standard SIL determination techniques in accordance with IEC6511 [3] can be problematic.

8.6.5 Determining fire and gas detector requirements and locations

Industry practice for determining detector requirements and locations is generally based on the specific rules and guidance developed in company codes of practice (most notably Shell and BP). BS EN ISO 13702 [1] also contains high level advice on detection systems and more recent developments include the ISA guidance on a risk based approach to fire and gas detection [15]. The HSE has also produced guidance on the selection and use of flammable gas detection [16], including recommendations on the alarm and executive action settings.

The specification and location of fire and gas detectors should follow a structured approach including the following steps:

- Completion of a fire and explosion risk assessment.
- Identification of areas of concern and release scenarios.
- Analysis of consequences and hazard frequencies.
- Determination of size of fire to be detected.
- Development of detailed performance requirements.
- Development of the detailed coverage requirements (i.e. percentage coverage by multiple and single detectors).
- Flammable gas detector location basis; the use of a grid based on 5 m spacing for point detectors has proven successful in detecting releases.
- Final validation of coverage and achievement of performance requirements.

There are many suppliers who will undertake fire and gas requirements, determination and mapping on behalf of a project or duty holder and an increasing number of 3D environment mapping software tools are available.

In addition, the location of the gas detectors should take into account:

- Leakage sources within the area and areas for potential gas accumulation.
- Potential gas or vapour cloud size.
- The gas or vapour composition, temperature (on release) and density.
- Access for maintenance and calibration of the detectors (so that they retain their performance standard).
- The location of personnel access and escape routes (to identify potential impairment).
- Open path gas detectors should be installed in locations where their paths will not be interrupted by routine operational activities.

Typically fire detector requirements and coverage are determined based on a grading of the hazards into the following; hydrocarbon processing areas with significant potential for escalation, hydrocarbon processing areas with a reduced escalation potential, non-hydrocarbon process, utility or storage areas and accommodation/office areas.

This grading designation is then used to determine the fire detection technology, detector coverage requirements and alarm response. Fire detector location should consider the following:

- Detector coverage should be achieved within vendor-specified horizontal and vertical viewing angles.
- Flame detectors shall have clear line of sight of higher risk fire hazards within their effective field of view.
- Safe access for maintenance of detectors would not otherwise be possible.
- Open path flame detectors should be installed in locations where their paths will not be interrupted by routine operational activities.

8.6.6 Fire and gas detection response and actions

Confirmed fire or gas detection should always initiate immediate and appropriate executive action in the form of shutdowns and, where applicable, blowdown. Most platforms have between 2 and 5 levels of shutdown, depending on the extent and location of detection.

A system that requires operations personnel to walk into a gas release scenario in order to investigate before initiating shut down of the process system is potentially dangerous and is not acceptable. The detection system should instead be designed to give remote indication of the development and/or migration of the scenario thus allowing personnel to stay well away from danger.

For flammable gas leak detection purposes, the first alarm level should be set as low as reasonably practicable, preferably no higher than 10% of the lower explosion limit (LEL), the second alarm level should be no more than 25% LEL [16].

Regarding initiation of deluge on confirmed gas detection, a study commissioned by the HSE [17] concluded that activation of deluge on gas detection could make a significant improvement in the level of safety.

Where provided, the fire and gas system should be designed to perform the following functions:

- Monitoring:
  - To detect hazardous accumulations of flammable gases/oil mist.
  - Where considered necessary, to detect leaks (e.g. near pump seals).
  - To detect fires at an early stage.
  - To detect ingress of smoke and flammable gas into places where they may present a hazard.
  - To permit manual initiation of alarm.
- Alarm:
  - To indicate the location of any fire or hazardous accumulation of flammable gaseous or oil mist.
  - To immediately alert people of possible fire or gas incident.
- Control action:
  - To immediately initiate appropriate executive actions.

8.6.7 Detector types

There are two principal types of detector that are commonly in use in offshore installations: heat, flame and smoke; and flammable gas detection instruments. The most significant for risk reduction are gas detection systems, since they give the earliest warning of hazardous situations. The HSE Offshore Safety Directive strategy is to promote the use of a combination of sensors, thereby giving early leak detection by acoustic detectors and identifying flammable gas cloud accumulation with the infrared type sensors.

8.6.7.1 Infrared point detectors

Infrared point detectors operate using a reference infrared signal and a measured infrared signal that has been passed through the area of concern. The difference between the two signals is measured and, where a hydrocarbon source is present, the measured signal has reduced infrared levels indicating that some infrared has been absorbed by the surrounding gas.

Infrared point detectors should be used where infrared line-of-sight (LOS) detectors are inappropriate, i.e. where congestion or space restrictions apply and where conditions prohibit the use of LOS such as in small enclosures or potentially in HVAC system inlets.

8.6.7.2 Infrared line-of-sight detectors

The infrared LOS detectors have a similar basis to infrared point detectors. LOS detectors have a path that the detectors operate over, whereas, point sensors focus on a point. A source and a detector are set up to send and receive infrared emissions and the distance in between is the path.

LOS detectors are the preferred detection type for gases with a recommended maximum path of 30 m under offshore conditions. To reduce spurious alarms and trips, a xenon lamp infrared source should be considered. To avoid stray solar radiation impacting on the sensors, east to west orientation should be avoided.

8.6.7.3 Ultrasonic leak detectors

Acoustic monitoring techniques use ultrasonic sensors to detect leaks based on changes in the background noise pattern. These sensors respond to the sound generated by escaping gas at ultrasonic frequencies. The ultrasonic sound level is directly proportional to the mass flow rate (leak rate) at a given distance.

For pressures above 4 bara, ultrasonic technology can detect leaks before significant accumulation of gases and, where appropriate, should be used in combination with infrared detection. This type of detection relies less on air movement and the orientation of the release for successful detection. Ultrasonic detection often results in false alarms, cannot readily distinguish between different gases and should not be used for liquid releases.

8.6.7.4 Catalytic gas detectors

Catalytic sensors identify flammable gases using oxidation principles and wire resistance. The gas is oxidised by a catalyst within the detector and the reaction releases heat. The heat changes the resistance of wires within the detector that triggers detection.

These are susceptible to poisoning by oil mist or chemicals and can drift if not regularly maintained leading to spurious alarms and/or shutdowns.

8.6.7.5 Hydrogen gas detectors

Electrochemical detection is commonly used for hydrogen detection. It is based on the gas reacting in the detector and causing a reaction that releases an electrical signal proportional to the gas release. When the release reaches a specified concentration, an alarm is signalled.

Electrochemical point detectors should be considered for rooms containing batteries; however, free venting is the preferred method for dealing with hydrogen gas levels.

8.6.7.6 Oil mist detectors

Oil mist detectors use a photoelectric cell to measure small increases in oil mist density. A fan continuously draws samples through a measurement tube; an increased reading and alarm will result if any sample contains excessive mist when compared to clean air.

8.6.7.7 Infrared flame detectors

Infrared flame detection is based on sensing emissions within the infrared spectral band. Triple infrared flame detectors compare three specific wavelength bands within the infrared spectral region and their ratio to one another, i.e. one sensor looks at a target range and the other two sensors look at ranges above and below to confirm if the signal is interference or a flame.

This type of detection can be used on all types of hydrocarbon liquid and gas fires. Best industry practice is to use multi spectrum infrared rather than single or dual spectrum. Multi-spectrum infrared increases the range and further improves differentiation of flame sources from non-flame background radiation such as sunlight, i.e. there is less signal interference.

8.6.7.8 Ultraviolet radiation detectors

Ultraviolet (UV) flame detectors sense emissions within the UV band of the electromagnetic spectrum. UV flame detection is only used where hydrocarbon gas is the only fire hazard. UV flame detectors are easily activated by false indications, have reduced sensitivity when the lens is contaminated/stained with oil and are not suitable for dense smoke or airborne oil droplets.

8.6.7.9 Combined ultraviolet and infrared detectors

UV and infrared detectors in combination sense emissions in both the UV and infrared range. If both sensors detect, an alarm is signalled. This type of detection makes infrared and UV false alarms less frequent, though, sensitivity is reduced since both UV and infrared wavelengths are required to reach alarm points.

8.6.7.10 Video Imaging Detection

Closed-circuit television (CCTV) can be used to detect emissions with wavelengths from 0.4 to 0.7 µm. The technology uses video detection and requires a high level of visibility, i.e. thick fog and smoke can block detection. Video imaging detection (VID) using CCTV is a relatively recent technology that lacks an established track record in industry.

8.6.7.11 Detection in HVAC ducts

Recommendations on flammable gas detection strategies for offshore HVAC ducts are listed below [18]. Projects should consider these recommendations when developing their gas detection strategies for HVAC ducts:

- Detector alarm levels should be set as low as reasonably practicable (10% LEL or less).
- Point catalytic, point infrared, extended path point infrared, cross-duct beam infrared and aspirated point detector systems all have the potential to be effective in detecting non-uniform distributions of flammable gas in and around HVAC ducts, provided that their sensitivity is sufficiently high (i.e. low detection limit) and that due regard is given to the possibility that gas will be distributed non-uniformly.
- Extended path point infrared detector systems currently appear to offer the greatest sensitivity, but multiple detectors should be used and sited so as to anticipate non-uniform mixing.
- Cross-duct beam infrared, extended path or aspirated point detector systems should be based on two beams or lines of aspirated point probes so as to ensure optimal coverage of the duct cross-section.
- In the absence of purpose-designed mixing elements no significant benefit from the perspective of gas mixing can be gained from siting detectors immediately inside an HVAC duct compared to locating them immediately outside the HVAC inlet.

8.6.8 Process relief, emergency shutdown and blowdown

Relief devices automatically release the contained fluid if the pressure within the system exceeds the system’s lowest design pressure. The relief system usually consists of relief valves or bursting discs and a route to vent the relieved fluids to an appropriate safe location, usually the flare system. Relief devices are designed to initiate at the set pressure without the intervention of the operator.

Blowdown systems are mechanisms for release of the vapour content from the system as a result of operator action or as part of automatic control sequences. A system is normally blown down as part of a planned shutdown or in an emergency such as confirmed fire. In both relief and blowdown systems, it is necessary to dispose of the contents safely usually via the flare system.

There are numerous references that discuss relief devices and relief sizing; examples are Parry (2004) [19], DIERS (1992) [20], CCPS (2003) [21], CCPS (2012) [22] and the Energy Institute (2001) [23]. Roberts et al. (2000) [24] have reviewed the literature available (up to 2000) on the response of pressurised process vessels and equipment to fire attack in regard to the new data available since publication of the IGNs [25] and the remaining gaps in knowledge.

8.6.8.1 Relief

API 520 (Part 1) [26] applies to the sizing and selection of pressure relief devices used in refineries and related industries for equipment that has a maximum allowable working pressure of 103 kPag or greater. The pressure relief devices covered in this standard are intended to protect unfired pressure vessels and related equipment against overpressure from operating and fire contingencies. It can be applied using heat inputs derived from ISO 23251:2007 [27]. The fire-sizing equations in Clause 5 assume typical in-plant conditions for facilities within the scope of API 520 [26] but can underestimate the heat input for vessels in partially enclosed or enclosed areas, such as those in buildings or on offshore platforms.

Energy Institute guidance [23] provides an alternative approach based on analytical methods and can be used to model fire heat input for all types and sizes of fire. To use these methods for fire relief calculations, it is necessary to specify the average fire temperature, rather than the instantaneous peak temperature. It should be recognised that pressure relief would not protect a vessel or pipeline from failure if there were a high heat load to a wall in contact with gas or vapour, as this will rapidly heat up to a temperature where the steel weakens.

There are a considerable number of standards for relief valve sizing e.g. API 520 [26], NFPA 30 (2015) [28] and NFPA 58 (2014) [29] (for LPG) and ISO 4126 (2003-2014) [30]. The Energy Institute (2001) [23] gives recommendations based on experimental data, for the safe and optimum design of relief systems. Their publication also goes into detail on which is the most appropriate relief device for the different situations. In particular, they consider the advantages and disadvantages of using:

- Conventional spring-loaded relief valves
- Balanced relief valves
- Air assisted relief valves
- Buckling pin valves
- Bursting discs
- High integrity pressure protection systems (HIPPS)

They provide advice on relief system design, sizing of relief systems, and design of flare and vent systems. In general, the recommendations complement those of API 520 [26] and ISO 23251:2007 [27].

8.6.8.2 Relief sizing

The method of relief sizing depends on the nature of the fluid being relieved. API 520 (Part 1) [26] and ISO 23251:2007 [27] give equations to calculate the discharge areas for pressure relief devices on vessels containing supercritical fluids, gases or vapours and for non-flashing liquids. The Energy Institute (2001) [23] have reviewed these equations and suggest that they give similar results to ISO 4126 [30] and hence the latter may be used.

Based on comparisons with experimental data, the Energy Institute (2001) [23] suggests that the homogeneous equilibrium model (HEM) gives the best predictions for two-phase relief flow. They suggest that the HEM method deals naturally with cases where the flow upstream is gaseous and where condensate is formed. Whilst the HEM method for two-phase relief has been validated by tests, there is still no recognised procedure for certifying the capacity of pressure relief valves in two-phase service.

8.6.8.3 Emergency shutdown

The ESD system provides the means of isolating the installation from import and export pipelines and providing inventory boundaries in topsides processing equipment. This minimises the available inventory in a loss of containment event and can quickly terminate import/export in the case of a pipeline or riser leak.

The PSR regulations [31] require ESDVs to be fitted to pipelines connected to offshore installations. The ESDV should be capable of stopping the flow of fluid within the pipeline. However, minor internal leakage past the ESDV may be accepted providing it does not represent a threat to safety. The rate of leakage should be assessed based on the installation's ability to control safely the hazards produced by such a leak and should form part of the appropriate performance standard.

Actuated isolation valves should be installed at appropriate locations throughout the plant to shut off the flow of fluids and to divide the process systems into discrete inventories. The location of inventory isolation should be selected with reference to the hazard presented and potential escalation consequences arising from a loss of containment of that inventory. Typically, isolation is provided between equipment or systems that have different design pressures and between process systems with large hydrocarbon inventories.

Platform wells should be isolated by closure of wing, master and surface controlled subsurface safety valves as appropriate.

ESD is typically initiated by either of the following events:

- Automatically by confirmed alarms from the fire and gas detection system.
- Process operator via manual shutdown in the central control room or at strategic locations across the installation.

The installation should be shut down in a controlled manner and the system divided into priority shutdown levels, (typically anywhere between 2-5 levels), according to the detected extent of the emergency situation. A typical hierarchy for a complex installation in ascending order of priority might be:

- Single process unit shutdown and inventory isolation.
- General process shutdown and inventory isolation including isolation from import/export systems and blowdown of specific systems.
- Platform shutdown including complete blowdown of process inventories.
- Platform shutdown including all power except critical communications and evacuation systems.
- Complete platform shutdown and the abandon platform alarm.

The system hierarchy should be such that initiation of a higher priority shutdown executes all levels of lower priority.

8.6.8.4 Blowdown

The blowdown system rapidly transfers any hydrocarbon gas and flashing liquids inventory to the flare system in a controlled manner and has two functions:

- To reduce the extent and duration of an initial fire, and thus reduce escalation potential.
- To reduce pressure within vessels potentially impacted by external fire to prevent vessel failure and consequent BLEVE.

API 521 [32] recommends that a vapour depressurisation system should have adequate capacity to permit reduction of the vessel stress to a level at which stress rupture is not of immediate concern. For pool fire exposure, this generally involves reducing the equipment pressure from initial conditions to a level equivalent to 50% of the vessel design pressure within approximately 15 minutes. This criterion is based on the vessel wall temperature versus stress to rupture and applies generally to carbon steel vessels with a wall thickness of 25 mm or more.

Blowdown will protect most vessels under fire attack against the risk of a BLEVE but there are exceptions, notably:

- Jet fire impingement.
- Thin walled vessels that may fail earlier than the basis set in API 521.
- Vessel saddles and supports may need additional protection.

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 failure of the vessel with catastrophic consequences. Gayton and Murphy (1995) [33] suggest that in more severe fires, rupture can occur well within the 15 minute criterion used by API 521 [32]. Roberts et al. (2000) [34] discuss applications of the Shell BLOWFIRE program to give vessel wall temperature-time relationships as input to the ANSYS finite element program predicting thermal mechanical response of a second stage separator with a wall thickness from 16 to 20 mm. The BLOWFIRE predictions were that after an initial pressure drop on opening, the pressure could then increase and the ANSYS programme suggested that failure could occur at 6 minutes. It was suggested that the worst case might be partial fire engulfment where local heating of the shell causes local material expansion and the expanding material pushes against colder, unheated sections, leading to premature buckling and an increased probability of failure. The general implication is that process plant fitted with blowdown systems designed to API 521 [32] or a similar standard may be insufficient to prevent failure of the pressure system before the inventory has been safely removed in severe fire impingement scenarios.

Current practice is for pressure vessel survival to be analysed in design to demonstrate that the overall depressuring objective of API 521 [32], of a vapour depressurising system that has adequate capacity to prevent vessel failure before completion of the blowdown process, will be achieved. Where this is not the case and there is a significant escalation potential then the vessel should be further protected preferably by the application of PFP or consideration given to faster depressurisation.

With regards to the blowdown system objective of minimising the escalation potential in the event of a detected gas release or fire then consideration may need to be given to the application of PFP or additional fire separation to related systems including:

- Staged blowdown systems.
- Flare headers routed through hydrocarbon processing areas.
- Potential trapped inventories that cannot be blown down, i.e. between isolation valves.

8.6.8.5 Blowdown system design

As indicated above, the ISO 23251:2006 approach to the design of blowdown systems covers most of the key aspects but may underestimate the heat load in some credible offshore fire scenarios and may not be accurate if there is two-phase flow. The Energy Institute [23] recommend that the Gayton and Murphy [33] 'fire risk analysis' approach is adopted at least to confirm the expected thermal loads and that the HEM method is used if two-phase flow is anticipated. The Energy Institute summarised the Gayton and Murphy approach:

- For each item of equipment, define the type of fire (pool, jet, partial or total engulfment) likely to affect it.
- Calculate the rate of heat input appropriate to that type of fire.
- Calculate the rate of temperature rise of the vessel wall neglecting heat transfer to the contents. This simplification is appropriate for jet or other fires, which might affect only a small area of the vessel. More complex methods can allow for heat transfer to the contents.
- Estimate the time to vessel rupture. From this temperature-time profile, prepare a yield –stress-time profile and a corresponding rupture pressure-time profile. Compare this to the actual pressure vessel versus time for the required blowdown time.
- If the time to rupture does not meet the established safety criteria (such as time to evacuate), then design changes may be necessary to improve the vessel protection. These may be a reduction in blowdown time, or application of fire protection insulation, or changes to the plant layout to reduce the fire exposure.

The information given in this guidance allows the simplified vessel wall approach to heat transfer to be followed, but if heat transfer to the contents is taken into account then sophisticated modelling is required. However, whilst there are validated models for blowdown under ambient conditions (e.g. the BLOWDOWN model), there appear to be no experimental data on blowdown under fire loading and hence there are no validated models. However, LPG tank pool fire (Moodie et al., 1998 [35]) and jet fire data (Roberts and Beckett, 1996) [36] has been used to partially validate models, e.g. BLOWFIRE, that are designed to cover a range of discharge devices i.e. the models have been used to predict the pressure relief results. API [32] and the Energy Institute [23] give the equations for calculating the blow down orifice.

In 2003, the Energy Institute published their interim guidelines for the design and protection of pressure systems to withstand severe fires [37]. In this publication, the heat transfer to the vessel is split in terms of radiative and convective fractions and the heat transfer to the vessel contents is discussed in a similar way. They give an iterative procedure based on calculating, for each process segment (isolatable section) and each time step:

- Pressure.
- Temperature in all fluid phases.
- Fluid composition in each phase.
- Flow rate through the orifice.
- Liquid levels.
- Temperature in the metal.
- Temperature downstream of the orifice.
- Heat transfer at all interfaces.
- Stresses to which the pipes and equipment are exposed.

These are related to the:

- Acceptance criteria for failure.
- Given total capacity of the flare system.
- Method for initiating depressurisation (manual or automatic).
- Time delay for initiation of depressurisation.

The Energy Institute approach is based on that of Hekkelstrand and Skulstad (2004) [38]. They have refined their approach with the emphasis on using fast depressurisation making the maximum use of the flare stack capacity and on minimising the use of PFP.

8.6.9 Functional safety

8.6.9.1 General

IEC61511 [3], sets out practices in the engineering of systems for the process industries that ensure the safety of an industrial process through the use of instrumentation. This standard outlines a functional safety lifecycle phase approach from initial hazard and risk assessment through to decommissioning identifying the objectives of each phase. Table 20 is an extract IEC61511- Part 1: Framework, definitions, system, hardware and application programming requirements.

Table 20: SIS safety lifecycle overview

Safety Lifecycle Phase	Objectives	Inputs	Outputs
Hazard and Risk Assessment	To determine the hazards and hazardous events of the process and associated equipment, the sequence of events leading to the hazardous event, the process risks associated with the hazardous event, the requirements for risk reduction and the safety functions required to achieve the necessary risk reduction.	Process design, layout, manning arrangements, safety targets.	A description of the hazards, of the required safety function(s) and of the associated risk reduction.
Allocation of safety functions to protection layers	Allocation of safety functions to protection layers and for each SIF, the associated SIL.	A description of the required SIF and associated safety integrity requirements.	Description of allocation of safety requirements.
SIS safety requirements specification (SRS)	To specify the requirements for each SIS in terms of the required SIF and their associated safety integrity, in order to achieve the required functional safety.	Description of allocation of safety requirements.	SIS safety requirements. Application program safety requirements.
SIS design and engineering	To design the SIS to meet the requirements for SIF and their associated safety integrity.	SIS safety requirements. Application program safety requirements.	Design of the SIS hardware and application programme in conformance with the SIS safety requirements. Planning for the SIS integration test.
SIS installation commissioning and validation	To integrate and test the SIS. To validate that the SIS meets, in all respects, the requirements for safety in terms of the required SIF and their associated safety integrity.	SIS design SIS integration test plan SIS safety requirements. Plan for the safety validation of the SIS.	Fully functioning SIS in conformance with the SIS safety requirements. Results of SIS integration tests. Results of the installation, commissioning and validation activities.

Safety Lifecycle Phase	Objectives	Inputs	Outputs
SIS operation and maintenance	To ensure that the functional safety of the SIS is maintained during operation and maintenance.	SIS safety requirements SIS design. Plan for SIS operation and maintenance.	Results of the operation and maintenance activities.
SIS modification	To make corrections, enhancements or adaptations to the SIS, ensuring that the required SIL is achieved and maintained.	Revised SIS safety requirements.	Results of SIS modification.
Decommissioning	To ensure proper review, sector organization, and ensure SIF remains appropriate	As built safety requirements and process information.	SIF placed out of service.
SIS verification	To test and evaluate the outputs of a given phase to ensure correctness and consistency with respect to the products and standards provided as input to that phase.	Plan for the verification of the SIS for each phase.	Results of the verification of the SIS for each phase.
SIS Functional safety assessment (FSA)	To investigate and arrive at a judgement on the functional safety achieved by the SIS.	Planning for SIS/FSA/SIS safety requirement.	Results of SIS/FSA.
Safety lifecycle structure and planning	To establish how the lifecycle steps are accomplished.	Not applicable.	Functional safety management plan.

Within a project, the following activities should be undertaken following the completion of the hazard and risk assessment studies and the HAZOP:

- Undertake reviews to define each instrumented protection function's reliability requirements (i.e. SIL/EIL/AIL Determination) using an appropriate technique, e.g. risk graph analysis (RGA), LOPA or fault tree analysis (FTA).
- It is common practice to undertake SIL determination during a combined HAZOP/LOPA review; this has the advantage that the discussion around failure causes and consequences are raised during the HAZOP and consistently applied to the LOPA by the same team members.
- Perform process studies to define performance requirements including required system action times.
- Develop a SRS incorporating the information derived from the above studies suitable for issue to system designers.
- Design system and select suitably rated components.
- Perform and document the FSA in accordance with the steps in IEC61511 [3].
- Arrange for and document factory performance acceptance tests and commissioning tests and document the adequacy of the results.

8.6.9.2 SIL determination techniques

Risk graph is a semi-quantitative approach that has the advantage of being more efficient than LOPA where there are a large number of SIFs and can be used as a screen to identify those SIFs that require further risk reduction.

LOPA is a more detailed approach that allows for greater consideration to be taken of further independent protection layers (IPL) and is often the standard approach to SIL determination in project delivery. LOPA should be undertaken by a multi-disciplinary team consisting of:

- Chair experienced in the LOPA methodology.
- Operator with experience operating the process under consideration.
- Engineer with expertise in the process.
- Process control/Instrument engineer.
- Manufacturing management.
- Instrument/Electrical maintenance person with experience of the process under consideration.
- Risk analysis specialist.

8.6.9.3 Functional safety assessment

FSA is an investigation, based on evidence, to judge the functional safety achieved by one or more SIS and/or other protection layers. The FSA should be led by a suitably experienced individual who is independent from the design, operation and maintenance of the SIS.

Consideration should be given to carrying out FSA activities at the following stages:

- After the hazard and risk assessment has been carried out, the required protection layers have been identified and the SRS has been developed.
- After the SIS has been designed.
- After the installation, pre-commissioning and final validation of the SIS has been completed and operation and maintenance procedures have been developed.
- After gaining experience in operating and maintenance.
- After modification and prior to decommissioning of a SIS.

The number, size and scope of FSA activities can depend upon the specific circumstances. The factors in this decision are likely to include:

- The size and duration of the project.
- The degree of complexity.
- The consequence in the event of failure.
- The degree of standardisation of design features.
- The safety regulatory requirements.
- Previous experience with similar designs.

8.6.9.4 High integrity protection systems

A high integrity protection system (HIPS) is a SIS designed to prevent an unsafe condition from arising with a SIL rating of 3 or greater. In the oil and gas industries this often relates to excess pressure but HIPS may also act to prevent a range of scenarios including temperature excursions, and high or low vessel level scenarios.

Wherever possible full flow mechanical relief systems should be designed to safeguard against all overpressure cases caused by process excursions. Where this cannot be achieved an active containment system, such as a HIPPS may be used. The choice of system should be based on the potential hazards, credible excursions and the vulnerability of the systems at risk, bearing in mind that relief systems are semi-passive and that an active HIPPS has to achieve suitably high integrity and reliability.

In the case of overpressure protection a HIPPS is applied where the plant is not fully rated to the pressures to which it might be exposed in a fault condition and either there are no mechanical protective systems to prevent overpressure and potential loss of containment or, the mechanical system is not adequate to independently prevent loss of containment in the worst credible case scenario.

HIPS are worth noting as a special case of a SIS and may require further analysis, option appraisal, detailed FSA and justification of ALARP but should also be subject to the full lifecycle outlined in Table 20.

8.6.10 Drainage

Drainage systems play an important role in removing hydrocarbon spills from the immediate area of process equipment and limiting the spread and extent of pool fires. The drain system design should be carefully checked, specifically:

- Never mix separated produced water and drains in one caisson.
- Never allow process hydrocarbons into open drain systems.
- Note that water seals in drain systems are unreliable protection devices.
- Use of process pressure by operators to 'blow down' liquids to the closed drains system should be forbidden unless the system is specifically designed for this practice.
- Accommodation and sewage drains should be independent from any other drains.
- Deluge operation must be taken into account in drain system design.
- HAZOP of drain systems is essential on all hydrocarbon facilities.
- Drainage capacities must take account of the vessel inventories in their specific areas and the effects of bund systems.

Open drain systems are typically classified as hazardous and non-hazardous. It is important that segregation of the drain systems is maintained at all times to prevent migration of hydrocarbons into safe areas where they may present an ignition risk.

Seal pots and seal loops in the drain headers are used to provide segregation between drain systems. Measures should be in place to ensure that all seals remain liquid filled. Routine plant inspections should include checking that seals are intact and that no debris has collected to block drains or gullies. Vents or siphon breakers should be provided at vertical falls to prevent liquid being siphoned out of the seal. Segregation of the drains systems is also necessary at the drains caisson. Dip pipes for the non-hazardous drains should be lower than those for the hazardous drains, to prevent migration of gas.

Winterisation of drain lines (particularly across bridges) and seal loops may be provided to prevent blockage. Winterisation should be maintained in good condition, and its effectiveness assured. Through Management of Change the implications on the drain systems of the area classification of the installation should be addressed, e.g. an area with new equipment re-designated as Zone 1 or 2 yet still drained by a non-hazardous drain.

8.6.11 Ignition prevention

Given that the leakage of flammable materials cannot be totally prevented throughout the life of the installation, then a fire or explosion will only occur if the leak is ignited.

The ATEX (Atmospheric Explosion) Directives 94/9/EC [12] and 1999/92/EC [39] cover electrical and mechanical equipment and protective systems, which may be used in potentially explosive atmospheres (flammable gases, vapours or dusts). The term 'equipment' is defined as: 'any item which contains or constitutes a potential ignition source and which requires special measures to be incorporated in its design and/or its installation in order to prevent the ignition source from initiating an explosion in the surrounding atmosphere'. Also included in the term 'equipment' are safety or control devices installed outside the hazardous area but having an explosion protection function. 'Protective Systems' are defined as items that prevent an explosion that has been initiated from spreading or causing damage. They include flame arresters, quenching systems, pressure relief panels and fast-acting shut-off valves.

Fundamental to the design process for the management of ignition risks is the process of hazardous area classification typically in accordance with EI IP 15 [40] or IEC60079-10-1 [41]. It is then important to ensure that there is a rigorous process to ensure the correct selection of hazardous area equipment, installation by component personnel and final inspection prior to operation of the new asset.

The hazardous area classification process and associated dispersion distances assess reasonably foreseeable fugitive leaks and as such do not account for major releases arising from, for example, a failure of process equipment. For this reason, assessment should be made of the foreseeable hydrocarbon releases via gas dispersion modelling to determine whether extending the hazardous area beyond that stipulated by the standards is a reasonably practicable measure.

Best practice is to locate uncertified electrical equipment inside enclosed areas which contain no process plant and to which the air supply can be shut off if hydrocarbon gas is detected at the inlets. The location of non-certified electrical equipment in open deck areas should be either avoided or adequately justified, for example by gas dispersion modelling.

The following principles should be applied in the design process:

- All ATEX [12] applicable equipment in hazardous areas shall be certified. This is to cater for 'fugitive' leaks in accordance with hazardous area design codes.
- A gas cloud from a medium or large leak can, and will, drift outside hazardous area limits. Therefore, caution must be exercised in locating unclassified equipment such as generator sets, temporary pump skids, heating equipment etc. in 'safe' open locations around the installation.
- Gas detection in or adjacent to safe areas should lead to automatic de-energisation of uncertified electrical ignition sources.
- Plant should be suitably earthed and all operators trained in awareness of static spark risks.
- Equipment that provides an ignition source and is unacceptably close to release sources should either be located inside an enclosure with ventilation ducts that close off automatically on detection of gas, or be provided with some alternative form of protection.
- External ignition sources, such as ship exhausts, helicopters and lifeboat engines, also need to be considered in the design process.
- The ignition prevention philosophy for the platform should fully explain how the ignition risk is minimised.

Failure to ensure safe working practices and competence of all personnel involved in hazardous area equipment installation could result in the ignition of explosive gas or vapour clouds leading to injury, fatalities and the destruction of capital asset investments; IEC 60079-17 [42] provides guidance on the demonstration of competence to work on equipment in hazardous areas.

8.6.12 Heating, ventilation and air conditioning

HVAC has a key function in dispersing and controlling gas and vapour releases, for example, preventing gas clouds from coming into contact with ignition sources or diluting toxic releases such that they pose a lesser hazard to personnel. There are key design features that enable the HVAC systems to achieve these roles; some of these are listed below. It should be noted that where it has such functions the HVAC system would be designated as a SECE, the following needs to be considered:

- Locate HVAC intakes optimally with respect to gas releases and fire scenarios.
- Penetrations between hazardous and non-hazardous areas should be kept to a minimum and any penetrations for piping, cables, ducts, etc. should be adequately sealed.
- HVAC penetrations, fire dampers and ductwork should be of the same fire integrity as the boundary through which the ductwork passes.
- The duties of extraction systems from enclosed hazardous modules should be carefully considered; they may be required to provide effective extraction of gases or hydrocarbon vapours and their eventual exhaust point should not contribute further to any escalation.
- The continued operation of the HVAC system may be required to be safety critical (for example, for a control room within a process module following a gas release). Suitable safety measures to protect the system and ensure its continued function and survivability will be required.
- Determine the optimal ways to protect against gas ingress, e.g. by generating positive pressurisation in ‘safe’ areas or sealing the areas via the use of HVAC dampers. (Experience has shown that HVAC dampers are often difficult to access and may suffer from reduced reliability as they age. If used, access to and maintenance of dampers should be considered very carefully).

For information on the detection of flammable gas ingress into HVAC ducting see Section 8.6.7.11.

8.7 Consequence mitigation and escalation management

8.7.1 Structure and layout

The fire and explosion scenarios for the installation will have been identified in the FEED study. The impact of these should already have been minimised as far as possible by the implementation of ISD during the concept and FEED project phases. The project ISD process should have identified opportunities to reduce the risk to structures and critical equipment items; the additional following steps should be considered to reduce the escalation impact of any residual risks.

Key structural supports (or vessel hulls in the case of floating installations) either need protection against the residual risks or through the provision of redundancy in the design. The effects on the structure of external, as well as internal flaming in confined but ventilation controlled modules must be assessed; escalating fire effects can lead to progressive collapse of the topsides.

Structural redundancy, whilst costly in the short term, has other long term benefits, e.g. for collision protection, reducing inspection or protection against long-term structural degradation.

An open design of platform with appropriately designed fire and blast walls to segregate process and drilling areas from safer areas with higher occupancy is preferred. Wherever fire scenarios within enclosed modules are identified, early failure of structural items in the roof of the module is likely unless passive protection and/or a very high rate of deluge application is provided. The times to structural failure and the consequences in the absence of protection should be investigated between the structural engineer and the safety engineer.

Grated floors greatly reduce the pool fire risks and reduce explosion overpressures. Environmental legislation, however, forbids marine pollution by oil, so measures to prevent operational spillage must still be provided. Grated floors do not provide a barrier against jet fires or radiant heat, and an understanding of the lack of protective effect should be considered during scenario and escalation developments.

The structural design must provide for rapid egress and escape of personnel from the process areas to sea or to the TR. Space allowance for a diversity of escape routes is essential; primary escape routes should be based on stairways not ladders. The designated routes must take into account all of the potential fire scenarios to ensure a viable escape route in all cases.

8.7.2 Blast protection design

Section 7 deals with the assessment of structures, piping and SECEs with respect to explosion loads; this section will cover the approach to be taken within a project to minimise the risk of escalation arising from explosion loads.

Application of an ISD process within the project will identify opportunities to reduce the potential explosion overpressure in the event of an ignited release; including leak ministration, equipment layout and minimising congestion and confinement. FEED should determine the required fire zoning and blast wall locations. Consideration should be given to the management of the residual risk arising from explosion overpressure to determine the requirement of blast walls:

- What is the calculated design load for the area?
- What are the potential structural elements, equipment, etc. whose failure could lead to an escalation scenario?
- Are further steps possible to reduce the load or vulnerability of structures or equipment?
- Is specific isolation needed between high risk and low risk areas?
- What is the required location of blast walls?
- Ensure that the impact of further confinement on blast design loads is reassessed.

The key factor in the response of the structure or equipment to explosions is the limitation of escalation damage, or containment of damage. Measures to be considered under this category include:

- Minimisation of potential missiles.
- Strengthening or protection of critical safety systems/equipment.
- Protection or behaviour of the primary and secondary structures subjected to explosion loads.
- Deflection of decks.
- Behaviour and ultimate capacity of blast walls.
- Mechanisms of escalation.
- Stability of tall structures.
- Protection from loss of containment damage to process systems components. Further guidance on designing to minimise the risk of failure of process piping systems is provided in FABIG Technical Note 8 [43].

8.7.3 Passive fire protection

The PFP arrangements will take the form of structural barriers, insulation or fire retardant coatings and are used to protect critical equipment, walls, decks and structural members. They should be used to protect against defined credible fire hazards that are capable of causing failure, and should take into account the fire size, duration, location and intensity.

Passive methods are preferred where specific protection of critical process or structural items is needed in order to prevent escalation. Widespread application to process and structural items is not generally feasible due to weight, inspection and maintenance/replacement issues. The current design philosophy is to identify specific areas or items of concern (usually structure, vessels or piping which on failure would significantly escalate the initial event) and to target these items for PFP application. PFP is preferred over deluge in such situations since it is immediately available and is not reliant on any activation systems; hence, it is inherently safer. PFP can be effective in protecting vessels and other equipment against high pressure jet fires in situations where deluge will not provide sufficient wetting.

If properly applied/installed it is highly reliable in service. However, it has also been the cause of problems in the past so current best practice concerning the design and application of such systems, is discussed below.

PFP comes in many forms, but the object is always to provide a heat-insulating barrier between the fire and the item to be protected. PFP can be designed for use on vessels, pipework, structural members, boundary walls or individual items of SECEs. The objective is to prevent the protected item heating up and either losing strength, losing function, distorting or producing noxious fumes.

The basis of design should be to provide PFP systems appropriate to the specific fire scenario identified in the fire risk assessment. Any PFP provided needs to be specified to withstand an initial explosion in-line with the determined local area design accident load.

For any of the systems outlined below it is up to the designer to demonstrate initial suitability of the PFP system to the verifier and the HSE, and up to the duty holder to ensure the maintenance of the protection throughout the asset lifecycle. For some of the common systems initial suitability is easy to demonstrate since the manufacturer will have a standard fire test certificate (such as A60, B15, or H120) for the proposed system.

During the design process, it is important to identify through a systematic process based upon the fire risk assessment the requirement for PFP on key systems and items of equipment; key items to be considered include:

- Riser ESDVs (this is a regulatory requirement).
- Other key inventory isolation shutdown and blowdown valves.
- Process vessels containing high pressure process inventories.
- High pressure flare headers.
- Import/Export risers at risk from a loss of containment from adjacent risers, etc.

A selection of the various PFP technologies are discussed in the paragraphs below.

Cementitious or vermiculite type

These are heavy mineral-based based coatings that can be applied to walls, structure or pipework in a wide variety of ways from spraying or trowelling to bolting-on of pre-formed sections. They have been used extensively offshore since the 1970s. The thickness of the coating principally determines the time it takes to transfer the heat through the coating and the mechanical strength of the compound or sometimes an extra outer shell, determines whether the coating will withstand the physical impact of the fire, e.g. erosion from jet fire impingement or pressure waves from explosions.

Since the properties of cementitious or vermiculite coatings are well researched and many applications have been extensively tested, classification of the protection is easy to obtain. Some systems have been tested and found capable of withstanding the impact of high pressure jet fires.

Intumescent coatings

Intumescent paints and coatings work by expanding to many times their original thickness on exposure to high heat or flame to produce a fire resisting, thermally insulating coating or 'char'. As for the mineral-based coatings discussed above, they are available in a variety of forms to suit a wide variety of applications from protection of deck undersides to sealing of piping or cable transits.

The possibility of corrosion under PFP coatings is a major concern for designers. Although intumescent coatings can now be applied in fairly thin layers, use in underdeck or other exposed areas and particularly in the splash zone usually requires a thin neoprene layer under the coating and another on top to prevent external corrosion and protect the coating.

Other technologies

There are other more recently developed PFP technologies including syntactic foams and fire resistant rubber polymers that claim significant advantages over more established technologies.

Removable PFP, in the form of enclosures, jackets or blanket wraps are often applied in particular to protect critical key pieces of equipment such as ESDVs where regular maintenance access is required. These can be removed to allow corrosion checks and inspection/maintenance of the protected equipment; it is important to assure the competence of personnel tasked with the removal and reinstatement of PFP enclosures.

8.7.3.1 Firewalls

Dedicated firewalls are often used to physically separate fire areas. The basis of the separation and the specification of the firewall are dependent upon both the fire types and severities identified in the fire risk assessment, and the criticality and vulnerability of the equipment, systems or personnel in the area being protected.

There are several grades of pre-defined firewalls and a fire risk assessment will generally choose an acceptable defined standard rather than develop a bespoke standard (unlike designing a blast wall for explosion hazards). The firewalls' continued performance is highly dependent upon the preceding and succeeding events, not least how their integrity is maintained following an explosion event and an explosion overpressure resistance requirement will normally be additionally specified for the firewall system.

Where a firewall of any class is pierced for the passage of electric cables, pipes, trunks or structural elements or for other purposes, the 'penetration' must be arranged so that fire resistance standard of the division is not impaired. Similarly, any openings such as doors or other access hatches must match the integrity of the division when closed and in the case of doors be self-closing.

More information can be found in HSE guidance on the assessment of fire and blast barriers [44] and the Lloyds Register's rules for offshore units [45]. The table of classifications from the HSE document is reproduced in Table 21 below.

Table 21: Barrier ratings exposed to hydrocarbon pool/jet fires and cellulosic fires

Barrier Rating H = Hydrocarbon A/B = Cellulosic	Stability and Integrity Duration (minutes)	Insulation Duration (minutes)	Jet Fire Stability and Integrity Duration	Jet Fire Insulation Duration
H120	120	120	60	30
H60	120	60	60	30
H0	120	Not suitable	60	Not suitable
A60	60	60	Not suitable	Not suitable
A30	60	30	Not suitable	Not suitable
A15	60	15	Not suitable	Not suitable
A0	60	0	Not suitable	Not suitable
B15	30	15	Not suitable	Not suitable
B0	30	Not suitable	Not suitable	Not suitable

Source: http://www.hse.gov.uk/offshore/fire-appendix2.pdf

8.7.4 Active fire protection

Fixed AFP systems are based on firewater pumps feeding a firewater distribution network, the network can be supplemented by foam-concentrate systems (tanks and pumps feeding a foam-concentrate distribution network).

Deluge works by mitigating the effects of fires principally by providing cooling both to the fire and to equipment exposed to radiant heat from the fire. In addition it can wash away liquid fuel fires to drain systems or overboard. Protection of all the equipment in a module by application of PFP is rarely practical, so the alternative is to deluge a whole module or section of structure with large quantities of water. The water acts to:

- Cool the general area by evaporation of the smaller water droplets.
- Provide a running film of water onto equipment in the area in order to cool it.
- Provide a screen of water droplets as a barrier to radiant heat, thus reducing the heat load on structures and equipment.
- Provide a screen of water droplets as a barrier to radiant heat exposure of people.

- Retard the movement of the flame front through a module and consequently reduce explosion overpressures to some degree.

For general area cooling, the key factors are application rate and water droplet size. If the water droplets are too small, they evaporate rapidly in a severe fire or can be blown away if the area is exposed. If the droplets are too large then there is less evaporation from fewer droplets and the cooling is inefficient for the amount of water used. The droplets, however, are less affected by wind, will reach the floor, cool and wash liquid spills away, and can provide a running film of water over equipment to keep it cool. Larger droplets, however, require bigger pumps, more power, and more AFFF so the cost of the system has to be balanced against its effectiveness.

General deluge only protects equipment exposed to flame and/or radiant heat from pool fires or radiant heat from jet fires providing there is a sufficient deluge rate to provide a film of running water over the equipment. Where a jet flame actually engulfs equipment, however, much of the film is likely to be displaced by the jet flame and the cooling effect lost. Directed water deluge using high velocity nozzles may be considered as trials have indicated an increased effectiveness against jet fires.

Areas shielded from deluge but exposed to the fire will receive some limited protection from the heat attenuation of the deluge droplets falling between the location of the fire and the location of the equipment. Objects subject to thermal radiation from fires (but not direct fire impact) receive benefit from attenuation of the water sprays active between the location of the fire and the object.

Suppression of combustion and cooling of the high heat layer in the roof of a burning module (where the module is partially enclosed) is known to be achievable by spraying very fine droplets at roof beam height. At the present time, there is no method for calculating the protection provided by this mechanism,

The deluge rate and droplet size must be suitable for the cooling mechanism appropriate to the type of fire. Where there are several different scenarios, the deluge rate for the worst case scenario, should be used, as this should cover all lesser cases. Therefore, in the case of enclosed modules with potential for serious, pressurised oil, gas or condensate fires deluge rates of 20 to 24 $l\ min^{-1}\ m^{-2}$ would be needed, with rapid activation and water coverage especially at roof-level where the high heat will concentrate.

8.7.4.1 Deluge application rates

The deluge application rates recommended in view of the findings of research in the UK and Norway into the characteristics of confined hydrocarbon fires, are summarised below; Table 22 is an extract from information provided in European Standard EN ISO 13702 [1]; Table 23 presents typical deluge rates based on hydrocarbon fire type based upon the Fire Office’s Committee’s ‘Tentative rules for medium and high velocity water spray systems’ [46].

Table 22: Selection of active fire protection systems on typical areas

Area/Room	Type of Protection (in Addition to Portable)	Typical Minimum Water Application Rates (l $\min^{-1}$ m^{-2})	Comments
Wellhead/Manifold area	Deluge/Foam/Dry chemical	20 (or 400 l min per well)	Based on API 2030.
Process areas and riser balcony area for floating production units	Deluge/Foam/Dry chemical	10	
Pumps/Compressors	Deluge/Foam	20	Based on NFPA 15.
Gas treatment area	Deluge/Dry chemical	10	Foam if area contains significant flammable liquids.
Methanol area	Alcohol-resistant foam or deluge	10	Portable foam units, if the methanol area is small.
BOP area	Deluge/Foam	400	
Emergency generator room	Water-mist/Foam/Deluge	10	Effect of water on equipment in the room should be evaluated.
Fire pump room	Water-mist/Foam/Deluge	10	Effect of water on equipment in the room should be evaluated.
Helideck	Foam/Dry chemical	6	
Vertical and horizontal structures	Deluge	10 (4 l $\min^{-1}$ m^{-2} for horizontal)	
Evacuation and escape routes	Water curtain	15 l $\min^{-1}$ m^{-1} to 45 l $\min^{-1}$ m^{-1}	

Table 23: Typical deluge application rates by hydrocarbon fire type

Hydrocarbon Fire Type	Deluge Application Rate	Comments
Oil pool fires	10 l min^{-1} m^{-2}	Suitable provided the cause of the pool fire is not a two-phase (spray) release. Addition of AFFF is beneficial.
Hydrocarbon jet or spray fires (impingement)	General area deluge not suitable for protection of specific items against impinging jet fires.	Key items (e.g. riser sections, riser ESDVs, vessels with BLEVE potential) should be protected by other means (PFP or targeted, very high rate deluge).
Jet or spray fires (radiant heat exposure)	20 l min^{-1} m^{-2} General area cooling for plant exposed to radiant heat from jet fire in vicinity.	AFFF can help control residual hydrocarbon pool fires, but does not contribute to cooling of heat-exposed plant.
Well head fires	400 l min^{-1} m^{-2} per wellhead.	The objective is to prevent fire on one wellhead, affecting adjacent wellheads.
Gas-only jet fires	Where gas jet is large in comparison with size of module or installation, deluge may be of limited benefit.	This is often the case for small, open, normally unmanned gas platforms. A better approach could be based on rapid detection, isolation and blowdown coupled with PFP of key valves.
Directed deluge on tanks impacted by flashing liquid propane jet fires	100 l min^{-1} m^{-2}	Horizontal cylindrical storage vessels should be protected by means of open medium velocity sprayers, not less than 6 mm bore, operating at pressures between 1.4 and 3.5 barg and should have cone angles between 60° and 125°.

8.7.4.2 Mitigation by sprinkler systems

These are usually potable water filled systems and provided in areas where the fire risk is non-process related and, therefore, less severe (e.g. inside accommodation modules). They are activated by frangible bulbs, which release water directly from the sprinkler piping as soon as the bulb is broken by the heat of the fire in the area. Design is straightforward by comparison with deluge systems and is usually in accordance with the applicable NFPA standards [47].

8.7.4.3 Watermist systems

Water-mist systems are now commonly being used in turbine, generator or pump enclosures to replace Halon protection systems, which are no longer. The fine mist is injected intermittently from pressurised water reservoirs/cylinders in roughly 15 second bursts. The mist provides cooling and suppresses the combustion, which will be also be controlled by lack of air into the enclosure (provided there is no damage from explosion on ignition). In enclosed spaces, protection systems need to take account of manning regimes and hence should include warning systems to evacuate personnel as the mist systems are being armed.

Enclosure type fires tend to be non-installation threatening (but always need due consideration within the fire and explosion review process for the installation). The protection is usually automatic and provides immediate control. However, there are a limited number of mist-injection cycles available from the water reservoir and instruction/training for follow-up action by the personnel, e.g. fire team action and/or evacuation needs to be covered in platform emergency response plans.

8.7.4.4 Gaseous fire suppression systems

Gaseous systems are a common solution for fire suppression with a number of modes of operation such as reduction of heat, disruption of the combustion process, displacement of oxygen, or a combination of these. There are a number of proprietary gaseous suppression media and systems available.

A typical gas suppression system will consist of a fire detection system, suppression agent storage containers, agent release valves, agent delivery piping, and agent dispersion nozzles.

The specific requirements should be developed in the fire protection philosophy considering the fire hazards, equipment to be protected and risk of oxygen suppression to personnel in the area.

8.7.4.5 Manual firefighting

In most major fires, the AFP system primarily relies on automatic and remotely activated fire protection systems. Manual firefighting facilities are only relied upon where:

- The fire hazard is readily controllable.
- Evacuation in the event of escalation can be implemented very rapidly.
- The maintenance load of the safety equipment adds risks to the maintenance crews (as has been found in the UK Southern North Sea on NUIs).

Nevertheless, manual firefighting facilities (e.g. hydrants, hose reels and fire extinguishers) are often provided in all areas to permit rapid intervention on small fires or to support the rescue of injured or trapped personnel. Some areas, notably helidecks, will also have monitors and hydrants sited to provide adequate coverage.

8.7.5 Emergency response

The PFEER regulations [48] place obligations on duty holders to ensure that measures are taken to prevent fires and explosions, and protect persons from the effects of any which do occur; and secure effective response to emergencies affecting persons on the installation or engaged in activities in connection with it, and which have the potential to require EER from the installation.

It is important that all projects undertake an assessment of EER requirements to ensure that suitable provisions are provided in response to major accidents.

In an explosion event, at least one escape route must be available after the event for all survivors. For a manned platform, a TR or suitable safe mustering area must be available to protect those who survive the initial incident from any effects arising from escalation.

NORSOK Technical Safety [2] provides further guidance on the requirements for EER, the key points are:

- Escape routes should ensure that personnel can leave areas in case of a hazardous incident by at least one safe route and to enable personnel to reach the designated mustering area from any position on the installation.
- There shall be at least two exits to escape routes from permanently or intermittently manned area outside quarters and offices, leading in different escape directions.
- Escape routes on decks shall be provided with a non-skid, oil resistant coating in yellow (RAL 1023). On deck grating, two parallel 100 mm wide yellow lines shall be painted indicating the width of the escape route.
- Escape routes leading to a higher or lower level should be provided by stairways. Ladders can be used in areas where the work is of such a nature that only a few persons (maximum three) are in the area on short time basis.
- The purpose of the evacuation system is to ensure means of safe abandonment of the installation for the maximum POB, following a hazardous incident and a decision to abandon the installation.
- The preferred methods of evacuation for installations that are not bridge connected to a neighbouring installation are in prioritised order: 1 Helicopter, 2 Free-fall lifeboats, 3 Escape chute with life rafts.
- The minimum number of free-fall lifeboats in the main evacuation area available during a dimensional accidental event shall be corresponding to the maximum POB plus one additional boat to compensate for unavailability. PFEER states that should be sufficient TEMPSC places for 150% of the POB.
- The muster area and the access to the evacuation station shall be arranged and protected in order to evacuate the actual number of personnel in an organised and efficient way. Area allocation shall be 0.4 m^2 per lifeboat seat.

- The PFEER regulations require that duty holders make effective arrangements to enable persons who have to evacuate or to escape from the installation to be recovered or rescued to a place of safety.

8.7.6 Temporary refuge

The TR should provide for the protection of personnel against the effects of both fires and explosions and from other hazards arising from the loss of containment of hydrocarbons, i.e. smoke, toxic and unignited releases.

Decisions relating to the location of the TR in relation to fire and explosion hazards should apply the concepts of ISD and should be initially addressed at the concept phase in the asset lifecycle. There will be a practical limitation on the protection that can be provided against the blast effects of explosions; thus the objective should be to reduce the explosion blast effects on the TR to as low as reasonably practicable. This is probably best achieved by maximising the separation distance between the TR and the likely locations of explosions so far as is reasonably practicable.

Duty holders are required to ensure all foreseeable integrity threats (i.e. MAHs) are identified and their potential for TR impairment assessed. From this assessment, suitable and sufficient performance standards should be established for the components systems identified as safety critical. These elements and systems require adequate maintenance and inspection to sustain the specified integrity. Otherwise, the TR may fail to provide the protection required, during a major accident to prevent significant loss of life. Duty holders should also demonstrate that the TR has sufficient integrity to ensure that risk of impairment is ALARP. The level of unreasonable impairment is indicated in APOSC [49] as greater than 1×10^{-3} per yr. This value has been established as a surrogate for societal risk, and includes all events capable of preventing TR functionality within the established time required for its survival [50].

The key design considerations for integrity of the TR will be:

- Blast Resistance: the highest over pressure that the TR can withstand before critical structural loss of integrity occurs (by calculation at the design phase).
- Thermal Radiation Impairment: Where possible this defines the maximum intensity of radiation that the TR can withstand before its structure or, more likely, internal temperature results in impairment before a specified period of exposure. This also includes the provision and maintenance of appropriate PFP to internal or external surfaces of the TR to ensure adequate survivability.
- Internal effects impairment: this includes events such as fire (heat and combustion products) and cumulative effects arising from a major accident such as heat rise, O2 depletion and CO2 intensification [51].
- Other external events that impair the TR without affecting the integrity of the installation such as structural degradation and failure may include: helicopter crash and/or non-process fire; and vessel impacts at vulnerable locations that have sufficient energy to render the TR unfit to perform its primary function.

TR impairment frequency (TRIF) is the sum of all TR impairment event probabilities. This allows comparison with the surrogate societal risk criterion stated in APOSC [49]. It is foreseeable that a ‘porous’ TR is likely to be exposed to smoke, fumes and hazardous or noxious gases. Contaminated external air will mix with the air captured in the TR (from HVAC shutdown). Any contaminants carried with this air will begin to increase in concentration inside the TR as the two atmospheres gradually equilibrate. Eventually, the contaminants will reach the same concentrations inside and outside of the TR. It is assumed that once these contaminants reach equilibrium levels, persons inside the TR will become impaired. It is foreseeable that this could occur in less time that the stated endurance period.

The minimisation of TR impairment is dependent on the presence of adequate SECEs, including components and/or systems that should be identified, evaluated, specified, inspected and maintained to ensure that they meet specific performance standards.

8.7.7 Survivability of SECEs

The survivability of any identified SECE should be considered in the design process and steps taken to ensure that suitable protection is provided against foreseeable fire and explosion events. Key considerations are:

- Is the SECE required to operate following an ignited release and subsequent fire and/or explosion?
- For how long should it remain effective?
- To what fire and explosion events is it potentially vulnerable?
- What reasonably practicable measures can be implemented to ensure its survival?

8.8 Operational phase

8.8.1 Project operational handover

The project should ensure that information covering the full basis of safety with respect to all major accidents hazards should be handed over to the operational team to allow for the management and maintenance of all SECEs over the lifecycle of the asset.

8.8.2 Fire and explosion hazard management in operations

8.8.2.1 Introduction

The hazard management framework shown in Figure 27 applies throughout the lifecycle of an offshore installation. The principle fire and explosion hazards will have been identified and minimised, and the safeguards necessary to reduce residual risk to ALARP determined by bowtie analysis or other methods, in design. These safeguards will normally include both engineering systems and procedural controls and both must be maintained for risk to remain ALARP.

Most of the engineered systems needed to manage fire and explosion risk will be SECE as defined in SCR 2015 [6]. They may also be specified plant provided in compliance with PFEER [48]. While there are significant differences between the two regulations, the law requires in either case that these systems are properly maintained and that their continuing suitability is assured and verified. It is common UKCS practice to manage SECEs and specified plant together and the legal distinction between them is not discussed further.

8.8.2.2 SECE management

Guidance on the management of SECEs is available in reference [5]. This section does not attempt to duplicate that guidance but merely to present some key issues relating to SECEs in relation to the management of fire and explosion hazards and risk.

SCR 2015 defines SECEs as [6]:

> *such parts of an installation and such of its plant (including computer programmes), or any part of those –*
>
> *(a) the failure of which could cause or contribute substantially to a major accident; or*
>
> *(b) a purpose of which is to prevent, or limit the effect of,*
>
> *a major accident.*

8.8.2.3 SECE Identification

Management of SECEs normally commences at the design phase of a project. The first task to be performed should be an assessment of MAHs and risks. This assessment determines what SECEs are needed to manage the hazards.

A bowtie analysis will usually identify barriers that fall into one the following three groups:

1. Passive systems/equipment that will be effective in all cases provided they remain in place and maintained.
2. Active systems/equipment, typically requiring automatic action in response to the detection of an incident.
3. Procedural measures/activities that require personnel to be aware of an incident and act appropriately in response.

The passive and active system/equipment barriers are the SECEs. They can also be categorised according to their function in preventing or mitigating a hazardous fire or explosion event as follows, (note that some SECEs may contribute to more than one function):

- Prevention SECEs will normally include primary containment (process vessels and pipework), secondary containment (bunds, drains, etc.) of flammable materials, the structures supporting these and systems intended to prevent ignition.
- Detection SECEs detect that the prevention SECEs have failed and include fire, gas and leak detection systems that initiate alarms and/or automatic actions.
- Control SECEs aim to reduce the knock-on effects of an initial fire or explosion event, reducing its severity or duration and thus prevent escalation involving additional flammable inventories, critical structures or harm to people. Examples include ESD and blowdown systems, PFP and AFP, etc.

- Mitigation SECEs will include safeguards that prevent exposure to both initial and escalated events and include the TR, and PFP and AFP systems.
- Emergency response and lifesaving SECEs minimise the harm to people that may arise from failure of other SECEs, for example local alarms, systems to protect life and assist EER, emergency communications and emergency power.

8.8.2.4 SECE performance standards

Performance standards of SECEs are specified so that technical integrity can be assured and verified throughout the lifecycle of an installation. Performance standards will have been identified for each SECE during the design phase and will typically specify requirements in terms of:

- Hazard management goal
- Performance criteria for:
  - Functionality
  - Availability
  - Reliability
  - Survivability
  - Interactions
- Assurance activities
- Verification requirements

Each identified SECE performance standard should have clear measurable pass/fail criteria against which it can be assured and verified.

Assurance tasks will normally be carried out as part of planned maintenance routines. They typically involve physical checks of a defined parameter, a measurement of a value against a target or an assessment of the performance of the SECE against a desired standard to confirm that the performance criteria are being met. SECE assurance should be documented, describing the performance assurance activities with the unambiguous relevant pass/fail criteria.

Planned maintenance and assurance activities are commonly controlled by a computerised maintenance management system (CMMS) which has the capability to:

- Manage the maintenance programme so SECEs remain available, functional, reliable, and in a good condition.
- Monitor and analyse test, inspection and maintenance data of SECEs.
- Initiate mitigating actions in the event of failure/degraded performance of SECEs.
- Schedule SECE equipment uptime and downtime in order to maximise the mean time between failures (MTBF).
- Manage equipment repairs in order to minimise the mean time to repair (MTTR).
- Be able to accurately record SECE maintenance history, in particular the pass/fails.

Verification describes a second tier of checking carried out by in independent competent person to verify that an SECE continues to meet its performance standards and thus remains suitable in operational service.

8.8.2.5 SECE unavailability and impairment

It is inevitable that there will be times when an SECE is not fully available or its performance standard is not fully met. This may be due for example to:

- Deterioration or damage.
- Failure in service that is immediately apparent or discovered during planned maintenance checks as above.
- Planned outages to allow maintenance or repairs to be carried out.
- Bypass or inhibits required for testing, etc.

Pre-defined contingency arrangements may be in place for some common unavailability events but it is unlikely that these will describe the full range of possible scenarios. Therefore, it will be necessary to react to unexpected impairment events (and combinations of events) to develop risk-based solutions.

8.8.3 Operational risk assessment

Most operators apply a process of operational risk assessment (ORA) to determine the necessary actions needed in response to the unavailability or impairment of an SECE. This will typically involve a consideration of a range of factors to assess the risk arising from the impairment and identify further risk mitigation measures and actions that must be taken to minimise risk until the functionality of the SECE can be reinstated. Matters to be considered in ORA include:

- Criticality of the SECE function impaired.
- Nature and extent of the impairment.
- Operational status of the installation.
- Planned operations and maintenance.
- Condition and availability of other relevant or interacting SECEs.
- Other circumstances as relevant.

8.8.4 Cumulative risk assessment

OGUK has published guidelines [52] on the management of cumulative risk arising from MAHs. There is a recognition that management of each deviation individually may not ensure that the cumulative risk of many deviations acting together is effectively managed.

The guidance covers the assessment of the cumulative effect of multiple deviations when people, plant and processes adversely deviate from their normal state and the interactions between them. The guidance suggests a number of approaches and methods recognising that different cumulative risk issues may require different assessment methods.

8.8.5 Change management

Good industry practice requires that process and plant modifications should not be undertaken without having undertaken a safety, engineering and technical review to ensure that following implementation of a modification risks remain ALARP. This review should be traceable and clearly identify the changes proposed. A risk assessment should then be undertaken to identify whether:

- Any new hazards have been introduced.
- There has been a change to the extent of consequences arising from an existing hazard.
- There has been an increased in likelihood of realising a hazard risk.
- An existing SECE is being modified.
- There is likely to be a change to the demand on or performance requirements of an existing SECE.
- A new SECE has been introduced.

8.8.6 Ageing assets

Reference [53] addresses the management of ageing effects on SECEs and recommends that obsolescence and life extension issues should be incorporated in performance standards for SECEs such as structural integrity, process containment, controls and instrumentation, fire and gas systems.

Aging factors to be considered include:

- Robust structural, pipeline and process integrity management systems in place that account for ageing and possible life extension.
- Appropriate fabric maintenance of process equipment and structures is being carried out.
- Integrity management efforts should not exclusively concentrate on current and near future threats; long term plans should address ageing and life extension.
- Ageing and life extension are explicitly addressed in the performance standards; this should be subject to regular review, e.g. every five years.
- Audits should be performed to aid in the formulation of ageing and life extension protocols.

8.8.7 Production cessation and decommissioning

Decommission and dismantling of an installation needs to be considered, reviewed and implanted as a project following the majority of the steps within this guidance.

Dismantling of a fixed installation with a view to eventual decommissioning requires a specific revision of the safety case to take account of the particular hazards and risks involved. As plant is progressively decommissioned, the operational status and risk profile of the installation will change. The hazards will change, primarily due to the abandonment of wells and cessation of hydrocarbon processing and storage. The SMS may also need to be modified. The safety case needs to address each phase of the dismantling and decommissioning process [54].

Examples of matters to be considered include:

- A change to the basis on which the original safety case was accepted. This could mean hardware changes such as alterations to platform plant or a change in the management systems to accommodate dismantling activities.
- Human and organisation factors associated with dismantling and decommissioning activities such as the introduction of personnel to the platform who may be unfamiliar with established safety rules and expectations;
- The need to reassess the risk of MAHs as dismantling activities are progressed such as impact on detection (or similar) systems as they progress through different phases of the project. This will include consideration of alternative arrangements where necessary.
- Effect of work on emergency response arrangements including potential impact on lifeboat launching, work in the vicinity of the helideck, arrangements for exit routes being taken out of use, loss of communications systems etc.
- Impact on SECEs and associated verification scheme from dismantling activities, how this will be managed and level of verifier involvement required.

Once hydrocarbon production on an offshore installation has ceased, fire and explosion risks will typically reduce in stages as the installation is prepared for decommissioning and eventual dismantling.

Much of the decommissioning work for a floating installation will no doubt be carried out at the dockside but the detailed decommissioning programme for a fixed installation will depend very largely on the strategy to be adopted for topsides removal, i.e. single lift, modular lifts or offshore dismantling.

However, the preparations for decommissioning will comprise a number of steps typically including those below, which may be carried out in parallel, in a different order or at different times in different parts of the installation:

- Isolation of topsides from hydrocarbon reservoirs.
- Plugging and abandonment of wells.
- Isolation of topsides from pipelines, flowlines and risers.
- Mechanical isolation and water filling of pipelines and flowlines.
- Depressurisation of topsides hydrocarbon plant.
- Liquids removal from topsides hydrocarbon plant.
- Mechanical isolation (air-gapping), cleaning and gas freeing of hydrocarbon plant.
- Dismantling of process pipework and vessels.
- Dismantling and removal of drilling equipment.
- Decommissioning and removal of power generation plant.

Personnel will remain on the installation throughout these activities so the need to manage fire and explosion risk will remain. However, the nature and extent of the risk will change over the period, as will the criticality and extent of SECE coverage that is required. This means that the fire and explosion risks, and the SECEs specified in relation to these, will need to be kept under constant review as part of a management of change process.

Typically, it can be assumed that fire and explosion risks will change as follows as preparation for decommissioning proceeds:

- Jet fires – process hydrocarbon risk becomes negligible once process systems depressurised; diesel or avgas residual risk arises only from pumped systems.
- Pool fires – risk largely absent on process system draining; becomes negligible after vessel cleaning.
- VCE – risk remains until all process vessels and pipework hydrocarbon free.
- BLEVE – risk is largely removed on depressurisation and is absent process system draining.

8.8.8 Brownfield projects

In the UK sector of the North Sea, it is a requirement [6] that significant changes to an installation or its operation will require the safety case to be resubmitted; the submission should address a review of hazards including a reassessment of those arising from fire and explosion hazards and a demonstration that the risks remain ALARP.

Further oil and gas production developments are a common feature of the current industry and can be expected on nearly every asset at some point in its lifetime. Delivery of a major brownfield project should follow the same structured approach to hazard identification, ISD, mitigation and management set out in this chapter but there are particular constraints and considerations associated with brownfield projects, potentially including:

- Structural and weight limitations.
- Layout and space availability.
- New process temperatures and pressures out with the original design basis.
- Differing design standards between those in place when the asset was designed and current practice.
- Complex interfaces with existing process plant.
- Limitations in the capacity of utilities.
- Changes to the risk profile of the asset.
- Impact on existing EER arrangements.
- Construction undertaken on a producing asset.

These and other features can lead to a change in the fire and explosion risk profile and require project decisions that need to arrive at compromises whilst assuring the continued management of risks to ALARP [4].

Brownfield projects that introduce new hydrocarbon fluids onto an existing asset will by their very nature lead to an increase in platform risk; predominately this arises from:

- An increase in the asset hydrocarbon inventory.
- A change to the nature of the reservoir fluids (phase, flow, pressure or temperature).
- An increase in the number of leak paths (generally brownfield modifications will favour flanged connections due to the risk of welding in hazardous areas).
- Increased confinement as a result of the location of new equipment and/or new modules.
- Increased congestion arising from additional equipment and piping in existing platform areas.
- The introduction of hydrocarbon lines into areas of the platform previously hydrocarbon free.
- An impact on existing SECEs, and limitations in existing mitigation systems.

Considerations for the management of fire and explosion hazards during the execution of brownfield projects may need to include:

- Ensure that the concept selection phase considers the hydrocarbon fire risk and the confinement and congestion implications of options.
- Use of higher integrity flange connections to mitigate the impact of the increased number of leak paths.
- Use of current best practice instrument design to reduce hydrocarbon leak paths.
- Utilisation of new technologies not available at the time of the original platform design.
- Additional and/or improved fire and gas detection; acoustic gas detection or the introduction of flame detection.
- Lowering the level at which gas detection initiates executive actions and voting for executive action on a single detector.
- Initiation of deluge on gas detection.
- The removal of redundant equipment to reduce confinement and congestion.
- The relocation of equipment blocking vent paths.
- Enhanced robustness of small bore connections.
- Installation of HIPS to protect existing equipment against higher reservoir pressures and/or lower blowdown temperatures.
- Increase use of PFP for vessels and piping where the capacity of the current deluge system is limited.
- The review of existing SECEs for suitability with respect to the new or altered fire and explosion scenarios.
- Utilisation of past operational experience to reduce human error potential.
- Utilisation of past operational experience to improve inspection/maintenance regimes.

It is often the case on older installations that there is a clear conflict between the existing asset standards and the recognised current best practice. In these situations the new equipment and systems should, so far as is reasonably practicable, be designed in line with current standards; where this is not possible or leads to anomalous situations then a structured risk assessment approach should be established to ensure the continued demonstration that risks are managed to ALARP.

The HSE reference [55] states:

> *It should be borne in mind that reducing the risks from an existing plant ALARP may still result in a level of residual risk which is higher than that which would be achieved by reducing the risks ALARP in a similar, new plant. Factors which could lead to this difference include the practicability of retrofitting a measure on an existing plant, the extra cost of retrofitting measures compared to designing them in on the new plant, the risks involved in installation of the retrofitted measure (which must be weighed against the benefits it provides after installation) and the projected lifetime of the existing plant. All this may mean, for example, that it is not reasonably practicable to apply retrospectively to existing plant, what may be demanded by reducing risks ALARP for a new plant (and what may have become good practice for every new plant).*

8.8.9 Particular considerations for FPSOs

Floating structures for production, storage and offloading have been used safely and reliably throughout the oil industry for many years. Early installations were primarily floating storage and offloading vessels (FSO), but today the modern floating production, storage and offloading vessel, (FPSO), includes processing equipment and a higher level of sophistication. Consequently, the FPSO becomes an offshore producing installation, storage facility, and loading terminal all rolled into one unit. The FPSO and the FSO present many of the same hazards to personnel and the environment, although the added complexity of production facilities on the FPSO increases associated risk.

FPSOs usually consist of a marine structure supporting process and utilities decks of a more conventional offshore construction. These differing methods of construction are governed by differing regulatory regimes. For the UKCS, the application of SOLAS and MODU codes without demonstration of validation by the additional risk assessments normally required by PFEER will be insufficient for the treatment of fire and explosion events.

In general, FPSOs are unique in that they orientate themselves according to the relative forces of the current, wave and wind; this is called weather-vaning. Frequently the vessel will be positioned with the wind blowing lengthways from bow to stern. This is not the preferred arrangement from an explosion point of view, as a gas cloud will extend along the deck within congested areas rather than being blowout to the sides. However, it provides the opportunity for accommodation to be provided at the bow of the vessel, such that the path of a wind-blown smoke or a flammable/toxic gas plume arising in the process area is away from the TR and primary evacuation facilities.

The guidance in this section relies heavily on the published guidance of UKOOA [56] and the guidance issued by OGP [57].

A number of features impact fire related hazards on floating installations; for example, the geometry of the layout, compartmentalisation, operations, fire scenarios, response characteristics of marine construction to fires and the vulnerability of marine systems associated with the motion, station keeping and stability. The effects of fire on these features are discussed further below, some specific attributes to be considered on FPSOs are:

- Fire-fighting in the enclosed compartments containing marine systems (e.g. engine rooms, dynamic positioning control rooms, generators); firefighting techniques will include inerting, with the ramifications this entails for personnel access and the requisite alarms.
- As the process and utilities modules are normally located above the vessel deck (and the cargo storage), the process and utilities deck areas will be large, usually of one or two levels. Segregation to avoid escalation of a fire can be achieved by separation of modules occasionally further separated by fire barriers, (this may or may not help explosion overpressures but will impair the dispersion of released hydrocarbons).
- The fire risk analysis undertaken on FPSOs will consider the nature of the hydrocarbon fuel source as well. Due to the nature of the storage on FPSOs, the reservoirs where they are generally deployed tend to be crude that can be stabilised fairly readily. FPSOs may be required to hold stored product in their cargo tanks for typically 3 to 7 days dependent upon their geographic location; therefore, the FPSO solution is less favoured for more volatile reservoirs.
- The (potentially) long process and utilities decks and their orientation with respect to wind conditions will be affected by the weather-vaning of the FPSO. The top decks should be designed to follow a hazard gradient from the most hazardous area with respect to fires (and explosions) to the least hazardous. This will generally be from the turret outwards.
- Due to the weather-vaning effects (either due to wind or current and their effects on the superstructure height and hull draft); fires can escalate downwind and at the very least toxic products of combustion will be distributed downwind. The layout should consider these additional hazards and the design should accommodate them to maintain levels of safety. (Some designs have used dynamic positioning to adjust the FPSO orientation in the event of a release or a fire hazard; however, the dynamic positioning system then becomes a SECE and is subject to the development of performance standards and integrity assessments).
- On an FPSO, escape routes and piping runs may be very long and tortuous and personnel may need to pass the origin of the incident to reach the TR. Consideration in the design of escape over long distances during incidents and incident escalation should be a key issue.
- Fire water mains will also be extensive and distant from the fire pumps in the process area. Correct fire-pump sizing and firewater-main hydraulic analyses will be required to ensure adequate pressure at deluge points, hoses and monitors.
- Buoyancy, stability and station-keeping must be maintained at all times, and the systems associated with these duties must be protected from fire hazards.

FPSOs also require specific consideration of major fire hazard and release scenarios unique to their design and operation:

- Oil storage tanks – may present hazards in the form of either large-scale storage of stabilised crude or empty storage tanks containing potentially explosive atmospheres.
- Non-process hydrocarbon inventories – the FPSO can be a power-hungry installation and requires substantial storage of diesel to maintain station, process and utilities power demands plus other life-support systems. The vessels are often located in difficult or remote places and will generally be designed to be 'self-sufficient' for extended periods in the event that supply vessels cannot reach them.
- Jet fires on main deck – the process decks on FPSOs are often lifted clear of the cargo storage tank roof for several reasons (see bullet points below); a 5 m gap is not uncommon. The space provided allows jet fires from the underside of the process to reach other process or utility modules without any barrier to reduce the effect of the flame. The gaps provide other risk reducing and operational benefits but steps can be taken to reduce the likelihood of jet fires by careful layout and orientation of the higher pressure equipment.
- A gap will allow 'green water' to flow over the main deck without placing an excessive load on the process modules supports by creating restrictions and eddy current effects.
- A gap allows a clear and uninterrupted space for long piping runs (both process piping and storage tank vent and balancing lines).
- A gap allows personnel access across the vessel, both for normal operational and maintenance access as well as facilitating emergency response.
- Swivel connections are a potential source of releases. The turret contains a large number of swivel joints in order to function, these are often at the highest process pressure and pass the reservoir fluids prior to any cleaning or conditioning and are, therefore, subject to the FPSOs most onerous process duty.
- Offloading to shuttle tankers is a regular event and poses a significant risk both on the FPSO and the shuttle tanker (including sea surface fires). The risks arise from the breakage or leakage of the transfer hoses and the potentially flammable mixing of hydrocarbon vapours and air in the storage holds of FPSO and shuttle tanker. During the offloading operation, the shuttle tanker and FPSO are in relative proximity and the risks on either vessel are compounded by increased potential for escalation from the other vessel.
- There is a need to continuously vent hydrocarbon vapours during loading. It is important that the venting system be designed to accommodate the maximum volume of volatile organic compounds (VOCs) vented from storage. Allowance must be made for the potentially higher temperatures the vents will experience when venting during maximum production rates and as well as providing design allowances for possible process upsets. In some areas, local regulations or guidelines limit the amount of VOCs that may be released to the atmosphere; regardless it is always good practice to adopt loading procedures that will minimise VOC emissions.
- The atmosphere in the FPSO tanks needs to be maintained in a 'non explosive' condition. The normal method is to supply low oxygen content combustion products to the tanks from boiler uptakes or from an independent oil or dual fuel generator.

- Cargo tank purging must be carried out before introducing air to the tank to ensure that the atmosphere will at no time enter the flammability region. The guidelines given in ISGOTT [58] should be strictly adhered to during this operation.
- FPSOs need special consideration due to the potential venting of hydrocarbons either near the process plant or near the flare stack. Calculations will have to be made at the design stage to ensure that carry over of hydrocarbons from the inert gas stack will not interfere with day-to-day operations.
- It is recommended that the inert gas system complies in all respects with the requirements of SOLAS and the relevant IMO guidance notes. Prudent operators may also consider maintaining 100% redundancy for this critical component.

8.8.9.1 Combined Operations

Under SCR 2015 [6] a notification is required when an installation plans to engage in COMOPS. The COMOPS notification complements the existing safety case by (among other things), identifying any new or changed hazards arising from the combined operation, and describing how the installations' management systems will be co-ordinated to manage MAHs.

Notification is intended to ensure that adequate consideration is given to the hazards and risks arising from COMOPS, as defined in Regulation 2(4) of SCR 2015 [6], and that there will be effective co-ordination of management arrangements, including EER arrangements in an emergency.

Typically, an additional mobile accommodation unit will be connected by a gangway link to the offshore installation. When two or more installations are joined in this manner, there is a need to assess:

- Any change to fire and explosion hazards.
- Any change to the consequences that could arise from these hazards.
- Any increased or new escalation potential (including escalation between installations).
- Any increase in individual risk or potential loss of life assessment.
- The requirements of a suitable plan for emergency response should a major accident occur on either installation.

Given the need to minimise the impact on production it is often the case that the platform will be producing for periods of the planned COMOPS campaign and may not be hydrocarbon free at any point during the campaign.

Considerations for the planning stage of a COMOPS campaign with respect to MAH risks should include:

- The identification of opportunities to plan for and achieve an ISD solution; including a formal ISD review if appropriate.
- Location of the gangway on the platform; inherently safer locations with respect to hydrocarbon risks will decrease the risk of gangway impairment and may influence the decision on acceptable manning levels.
- The platform production and hydrocarbon free status throughout the campaign.
- Any change to the maximum POB and any phasing of this in line with production status.
- New EER provisions.
- Standby vessel and/or emergency response and rescue vessel requirements.
- The impact on the QRA of an increase in POB.
- Necessary platform manning levels and distribution to avoid intolerable potential loss of life (PLL) values.
- The impact of additional scaffolding and work equipment on the likely explosion overpressures and measures needed to manage this risk.
- The risk imposed on the mobile accommodation unit from a hydrocarbon release on the platform.
- Whether the accommodation unit represents an increased risk of ignition of hydrocarbon released from the platform.
- The detailed planning of simultaneous operations (SIMOPS) for the campaign, e.g. ensuring work on SECE is not planned at a time when other activities may place a demand on them.

A key part of any COMOPS EER [59] strategy is whether to take credit for the gangway and so relax the normal manning constraints for the operational facility. In setting manning limits, consideration should be given to:

- The reliability/availability of an evacuation method in the foreseeable events for which it is required.
- The diversity/redundancy in the form of backup evacuation means, e.g. evacuation to another jacket. In this case, the location of the alternative evacuation means in relation to the accommodation unit may be critical.

Normal operations manning restrictions recognise potential failure mechanisms in TEMPSCs and so ensure redundancy usually by the provision of 150% capacity. The presence of a gangway potentially negates the need for the primary evacuation needs to be by TEMPSC; they still provide the redundancy or secondary evacuation method, should the gangway be unavailable. As a result, analysis may demonstrate that the manning level can be increased up to the full TEMPSC capacity on the platform. Should the gangway availability be guaranteed in all foreseeable evacuation events (e.g. due to its location, or protection offered in its design) then reliance on TEMPSCs is removed and the manning level implied by EER provision could be lifted.

Appendices

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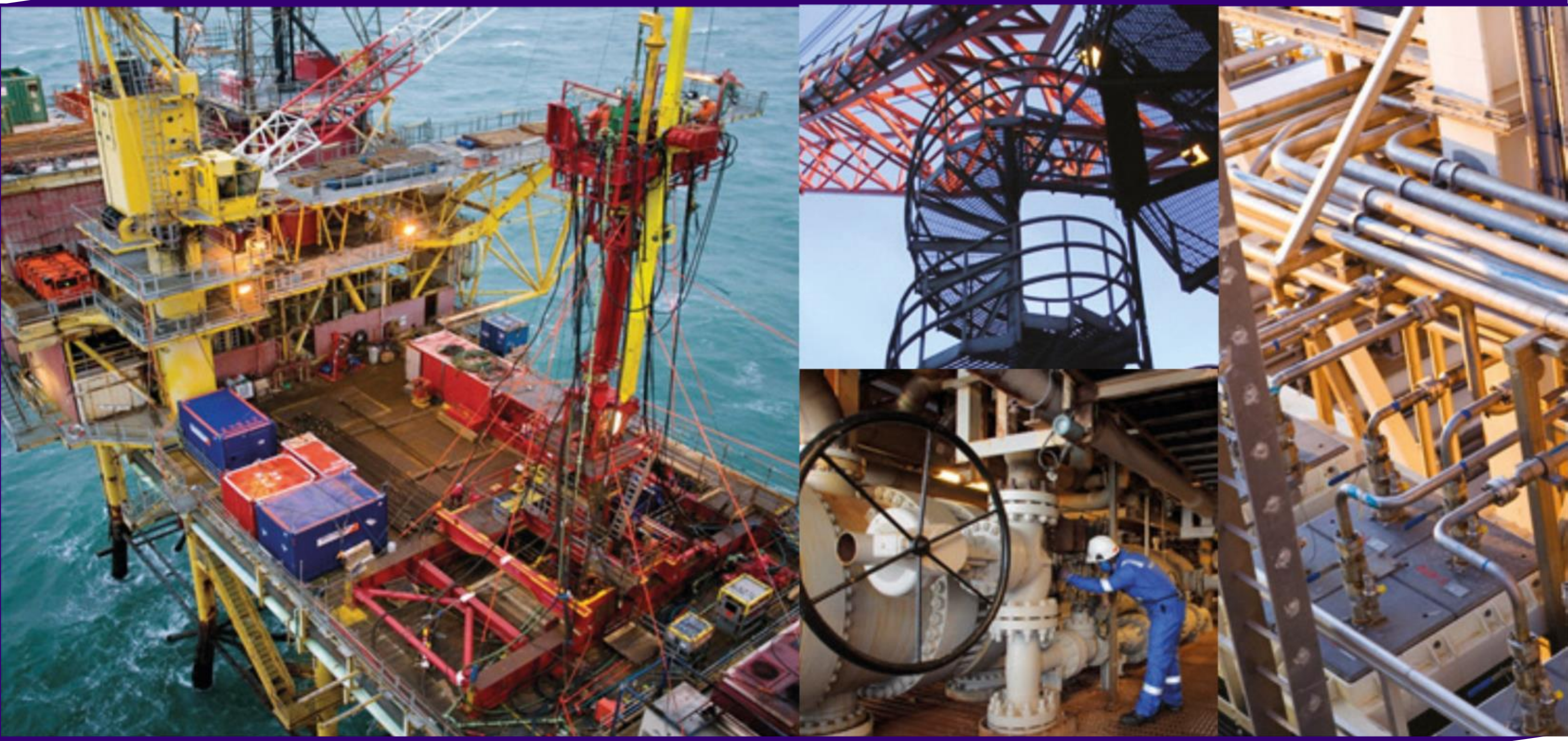

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ISBN: 1 903 004 73 2