Protection of piping systems subject to fires and explosions

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Protection of piping systems subject to fires and explosions

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This document aims to fill this gap by providing guidance on the protection and response of piping systems and piping supports subject to fires and explosions. The guidance covers the methods used to carry out both simplified design checks and advanced non linear analysis. It forms the background document to the FABIG Technical Note, to be published, on the protection of topside piping and piping supports against fires and explosions.

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FOREWORD

This work was prepared to fill gaps in existing knowledge on response of piping systems to hydrocarbon fires and explosions.

CONTENTS

EXECUTIVE SUMMARY

The principles of design of primary structure to resist loading due to fire and blast have been extensively described in recent literature including the Interim Guidance Notes and subsequent FABIG Technical Notes. In offshore structures, many of the principles applicable to the design of primary structure are also applicable to piping systems and piping supports. However, the subdivision of discipline design expertise in many cases results in poor transfer of the design technology from primary structural design to other disciplines.

This document aims to fill this gap by providing guidance on the protection and response of piping systems and piping supports subject to fires and explosions. The guidance covers the methods used to carry out both simplified design checks and advanced non linear analysis. It forms the background document to the FABIG Technical Note, to be published, on the protection of topside piping and piping supports against fires and explosions.

The original research, on which this document is based, was sponsored by the Health and Safety Executive and was carried out by The Steel Construction Institute.

1 INTRODUCTION

1.1 SCOPE OF THIS DOCUMENT

This document gives guidance on the protection of topside piping and piping supports against hydrocarbon fires and explosions.

In Chapter Two, the design basis for the protection of piping systems and piping supports against fires and explosions is presented.

Chapter Three provides more detailed guidance on calculating the blast load acting on piping systems and on determining the response of piping systems under explosion loading. Chapter Four provides similar guidance for fire scenarios and the ensuing structural response. Chapter Five presents guidance for the protection of piping supports against fires and explosions.

This document considers almost exclusively hydrocarbon fuel sources originating within hazardous modules. While it is primarily aimed at offshore modules, many of the recommendations are equally applicable to offshore oil and gas plants.

This document draws on the reports from:

Phase I Blast and fire Engineering Project for Topside Structures [1],
Interim Guidance Notes [2]
Phase II Report [3],
CMR Explosion Handbook [4],
Design of Offshore Facilities to Resist Gas and Explosion Hazard [5],
Explosion Loading on Topsides Equipment, Part 1 OTO 1999 046 [6]
FABIG Technical Note 6 High Strain rate and elevated temperature data [7]
Review of the response of process vessel and equipment to fire attack [8]
Guideline for the Protection of Pressurised Systems Exposed to Fire [9

These projects identified numerous critical gaps in our knowledge and understanding. This document is, therefore, by definition, interim and will become outdated and require updating as these gaps continue to be closed by the industry.

As much as possible, this document follows the same organisational layout as the IGN [2] and should be complemented by their use.

2 DESIGN BASIS

2.1 INTRODUCTION

This Chapter describes the hazard design philosophy for offshore platforms, and the corresponding safety management systems and performance measures. It also describes how this philosophy is applied throughout the life cycle of the platform using inherently safe design procedures. Issues pertaining to existing installation are highlighted. The procedures used for deciding when the risk becomes tolerable are described, and control and mitigation measures for the remaining risk are discussed.

2.2 GOAL SETTING APPROACH

It is useful to place the blast and fire strategy for piping within the broader context of the fire and blast hazard management plan for the platform, and in turn, to place that within the overall hazard managements system and to relate that to the goal setting approach used by the offshore industry. To this end, it is useful first to introduce the following definitions:

Goals: define the goal of the design

Safety management systems: that provide a plan to implement and achieve the goals

Performance Standards: to measure whether the goals have been achieved

Figure 1shows the relationship between the above three items, which are discussed in more detail in sections 2.2.1 to 2.2.3.

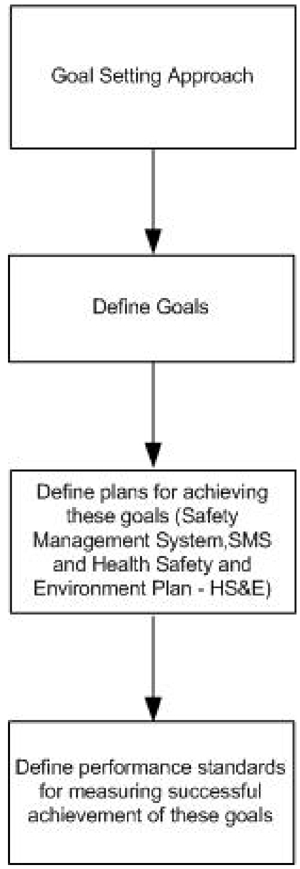


Figure 1 Goal Setting Approach

Figure 2 shows the five main stages in the life cycle of an offshore installation (concept design, Front End Engineering Design (FEED), detailed design, construction, and operation maintenance and control). At the early stages the information quality is low while the influence on design is high. However, at later stages when the quality of information becomes high, the influence on design is low. The Safety management system should address this issue.

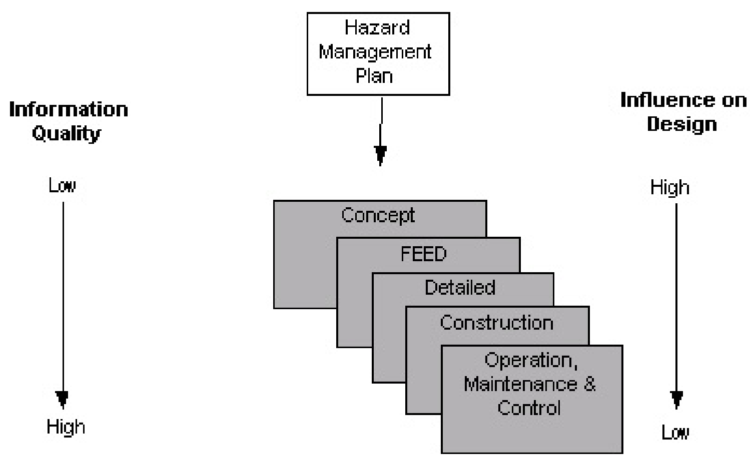


Figure 2 Outline of Life-Cycle

2.2.1 Design goals

The main design objective is to reduce the risk from hazards to as low as reasonably practicable (ALARP). Fires and explosions are two of the hazards for which this statement applies, and piping systems on topside structures are one of the issues that must be considered when considering fire and explosion hazards. For the purpose of reducing the risk from fire and explosion hazards to as low as reasonably practicable, the UKOOA guidelines on fire and explosion hazard management [10] identifies the following aims:

- Identify, analyse and understand all fire and explosion hazards and associated effects.
- The risk corresponding to fire and explosion hazards identified above should be as low as reasonably practicable
- A suitable order of priority, and a suitable combination, of prevention, detection, control and mitigation systems for fire and explosion hazards should be implemented and supported throughout the life cycle of the offshore platform
- The above prevention, detection, control and mitigation systems should have performance measures proportionate to the required risk reduction
- The design, operation and maintenance of the above prevention, detection, control and mitigation systems should be carried out by competent staff
- Any changes that may occur throughout the lifecycle of the installation, and that may affect the likelihood and / or consequence of any fire or explosion hazard event (and therefore may make the risk on the installation deviate from an ALARP state) should be identified and assessed. The prevention, detection, control and mitigation systems should be modified and updated as necessary to take into account any such changes.

The following additional goals, relating to piping systems, can be inferred from those outlined above:

- Prevent the build up of high pressures due to explosions, or
    - Minimise the frequency corresponding to severe explosions
    - Minimise the consequences of severe explosions
- Prevent the occurrence of severe fires, or
    - Minimise the frequency corresponding to the occurrence of severe fires
    - Minimise the consequences corresponding to the occurrence of severe fires
- Prevent the failure of safety critical piping in case of explosions and fires, or
    - Minimise the frequency corresponding to piping failure
    - Minimise the consequences of piping failure

2.2.2 Safety Management System

The safety management system provides a plan to ensure that the overall objectives for the management of all hazards and hazardous events (including those identified in section 2.2.1 above and corresponding to fires and explosions) are achieved. This overall management process is outlined in the E & P Forum "Guidelines for the Development and Application of Health, Safety and Environment Management Systems" and in the UKOOA Guidelines on Fire and Explosion Hazard management. Based on these two documents, the management process for fires and explosions hazards is achieved through safety management systems consisting of the following steps (Identify, Assess Reduce):

- Identification of the hazards
- Assessment of hazards
- Reduction of hazards based on inherently safe design principles, to reach a design solution where risk is ALARP

The safety management system is based on managing hazards and hazard effects throughout the life cycle of the project, from conceptual design through commissioning and operations to decommissioning. Fire and explosion hazard management throughout the life cycle of the project is an integral part of the SMS. Section 2.4 will discuss piping-specific hazard reduction measures for various stages within the life cycle of the installation.

2.2.3 Performance Standards

In the case of prescriptive rules, performance standards are not required since each duty holder would have to follow the prescribed rules. However, since the Piper Alpha disaster and the Cullen Report, there has been a move towards a 'goal setting' environment within the offshore industry. Performance measures provide a system of indicators that allow measurement of the successful (or otherwise) achievement of the goals.

The HSE document Successful health and safety management (HSG 65 [11]) states that setting performance standards are essential if policies are to be translated from good intentions into a series of co-ordinated activities and tasks. Performance standards should:

- Set out clearly what people need to do to contribute to an environment which is free of injuries, ill health and loss
- Help identify the competences which individuals need to fulfil their responsibilities
- Form the basis for measuring individual, group and organisational performance

Performance standards should link responsibilities to specific outputs, by specifying:

- Who is responsible
- What are they responsible for
- When should the work be done
- What is the expected result

The HSC Prevention of Fire and Explosion, and Emergency Response on Offshore Installations (PFEER)[12] regulations defines performance measures as:

> *A statement which can be expressed in qualitative or quantitative terms, of the performance required of a system, item of equipment , persons or procedure, and which is used as the basis for managing the hazard, e.g. planning, measuring, control or audit – through the life cycle of the installation.*

The UKOOA guidelines on fire and explosion hazard management [10] proposes a hierarchy of performance standards:

- *High level performance standards* which are applied to the installation as a whole and to major systems that constitute the installation

- *Low level performance standards* that are applied to measure the performance of sub-systems, whose performance may affect the high level systems that are measured using high level performance standards

In accordance with the goals described in Section 2.2.1 above, the level and number of performance standards should reflect the potential risk of the system whose performance they are intended to measure.

High level performance standards

These performance standards are meant to measure the goals for the safety of the installation and relate to the overall risk to the persons on the installation. Fires and explosions and their effect on the topsides structure and the topside piping will contribute to some of this risk.

The performance of the overall blowdown system, and the fire and explosion water deluge system will form part of the major systems whose performance is to be measured. Examples of such high level performance measures, related to piping systems, include:

- That the blow down system remain operational for an explosion event corresponding to a 10^{-4} return period
- That fire and explosion deluge system will be operational in case of explosion or fire corresponding to a 10^{-4} return period
- That piping containing flammable, explosive material will not fail, or will fail in a safe manner that will not lead to an escalation of an initial event.

Low level performance standards

Lower order performance standards should measure the performance of the elements and subsystems that comprise the blow down and fire and explosion deluge systems, and in turn contribute to successfully achieving the goals reflected by the high level performance standards.

Hierarchy of performance standards

As mentioned above, the safety case regulations require operators to provide information on performance standards for various tasks in the hazard management process. In addition to defining levels of performance standards in terms of low level or high level (as described above), it is possible to adopt a slightly different approach as described below (see Figure 2.3 [13]):

- Risk based performance standards which are quantitative and specify levels of individual risk, fatal accident rate, or similar quantities which have to be satisfied.
- Scenario based performance standards which can be either qualitative or quantitative, and which set an overall target or objective for the installation or part thereof and complement the risk based standard.
- Systems based performance standards that specify quantitatively a minimum level of competence or performance that must be demonstrated by personnel equipment, or design features under specified conditions. The scenario based and the system based performance standards are more difficult to determine. However three contributing factors to the establishment of these standards have been identified:
  - Functionality
  - Reliability
  - survivability

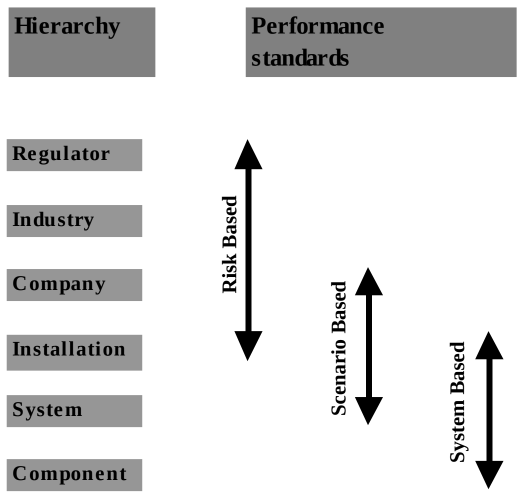


Figure 3 Hierarchy of performance standards

2.2.4 Guidance on ALARP Decisions

The concepts underlying ALARP are given in the HSE Reducing Risks, Protecting People (R2P2) document [14] and in the Guidance on ALARP for Offshore Division Inspectors [15]. Some of the main points are summarised below:

- Risk criteria and tolerability: The HSE framework for tolerability of risk shows three regions (see Figure 2.4):
  - A region of high risk, where the risk is unacceptable regardless of the level of benefit associated with the activity
  - A region of intermediate risk, where the risk can be tolerated if it can be proved that there is gross disproportion between risk and further risk reduction, and if there is a system in place to ensure that risks are periodically reviewed to examine whether further controls are appropriate
  - A region of low risk where no additional measures are necessary except maintaining usual precautions
- In the ALARP context, the duty holder is required to take into account the individual risk and the societal risk (risk of multiple fatalities)- bearing in mind that other aspects of societal concern have already been reflected in the regulatory regime in which the duty holder is operating
- The HSE guidance indicates that it is good practice (but not enforceable) to apply the principles of prevention as a hierarchy
- Good design principles aim to eliminate a hazard in preference to controlling the hazard, and controlling the hazard in preference to providing personal protective equipment.
- A holistic approach is important in order to ensure that risk-reduction measures adopted to address one hazard do not disproportionately increase risk due to other hazards, nor compromise the associated risk control measures.
- It is expected that new installation would not give rise to residual risk levels greater than those achieved by the best of existing practice.

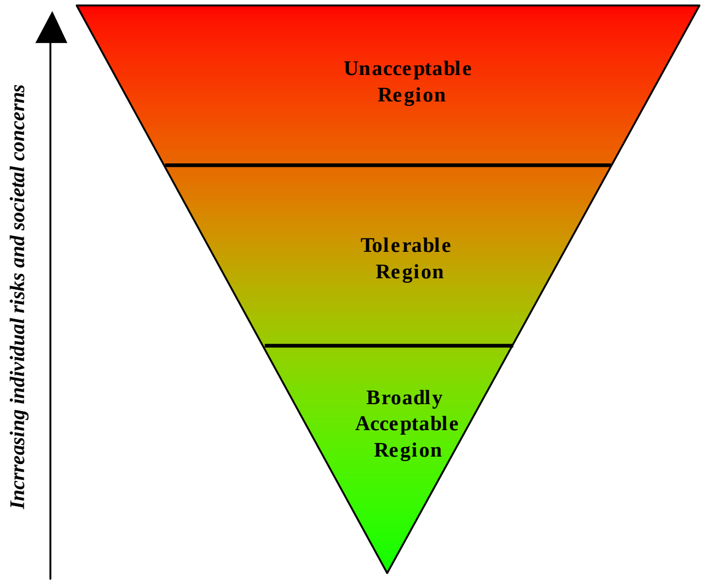


Figure 4 Risk Regions and ALARP

Throughout the life cycle of the installation from the conceptual stage to the operation and decommissioning stages, risks should be assessed and risk reduction measures should be carried out if the risks are not ALARP. However, the type of risk reduction measure that may be carried out will depend to a large degree on the stage within the life cycle of the installation. During the conceptual stage a wide variety of risk reduction measure are available including prevention and elimination while at later stages in the life cycle the majority of risk reduction measures available would fall under the control and mitigation categories. Figures 2.5 and 2.6 show the various categories of available risk reduction measures and their variation from least to most preferred, where it can be seen that inherent safety, to be discussed in the next section, is the most preferred risk reduction measure.

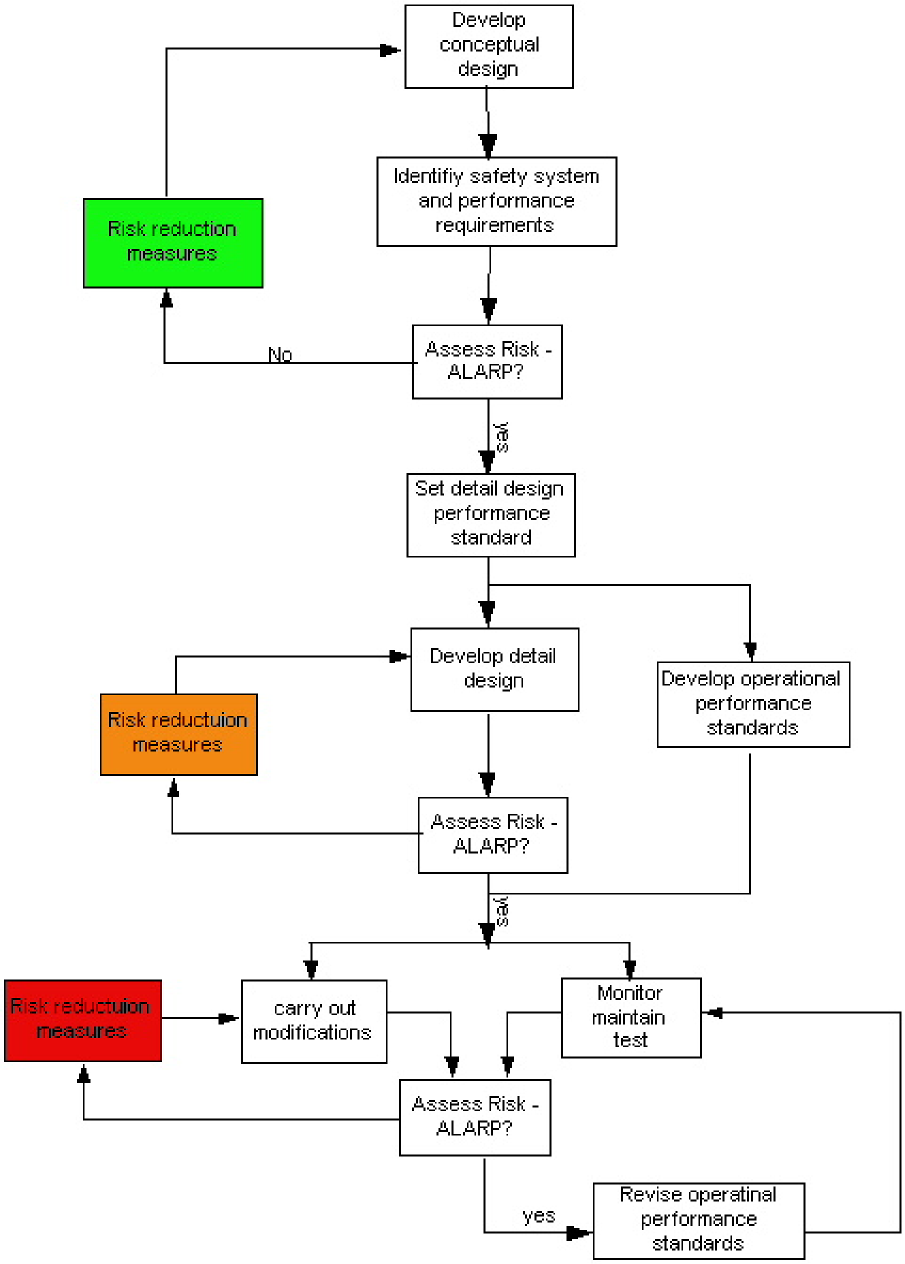


Figure 5 The application of risk reduction measures at various stages

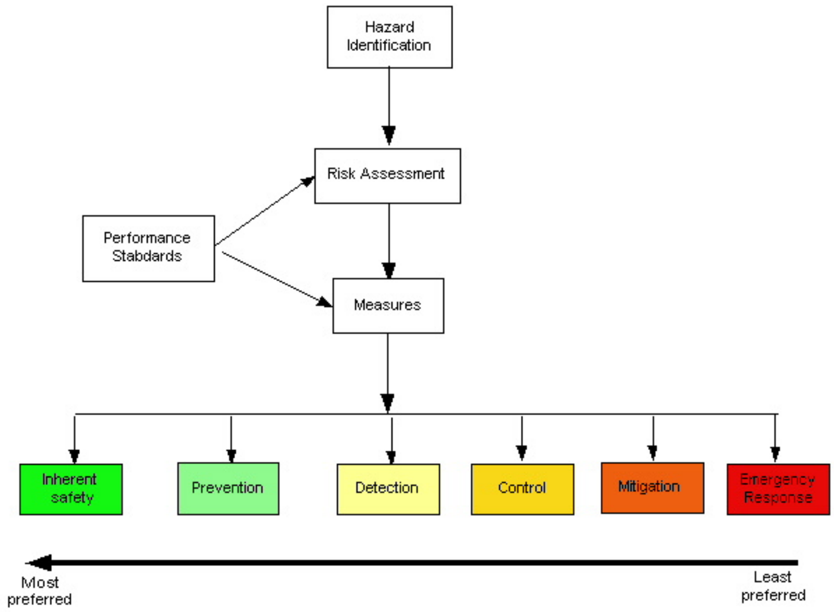


Figure 6 Types of available risk reduction measures

2.2.5 Inherent Safety

It is difficult to arrive at one clear definition of inherent safety. The Safety Case Regulations do not provide a clear definition of inherent safety. However, it provides several examples of how it should be applied, including:

- Substituting less hazardous for more hazardous processes
- Avoiding undue complexity in the design
- Allowance for human factors or control systems which reduce the risk of human error
- The design of vessels and pipelines to minimise the effect of sources of deterioration, to reduce stress concentrations, and facilitate inspection after construction and during operation.

OTO 98 148 [16], OTO 98 149 [17], OTO 98 150[18], OTO 98 151 [19] identify two alternative definitions of inherent safety:

- The first definition is related to design process- i.e. any activity which is carried out during the design to make the installation less vulnerable to environmental and man-made hazards. The effect of inherent design in this context is to reduce the likelihood of a hazard occurring, to reduce its consequence if it occurs, or in some other manner to reduce the risk associated with the hazard. Inherence in this context implies that vulnerability to hazards does not increase significantly over time, e. g. it is not dependent on repairs.
- The second definition is not tied to the design stage, and can involve steps taken at the construction, operation or alteration stages. However it is restricted in the sense that it refers to actions that may be carried out to prevent a hazard from taking place. In this context reducing the consequences of an incident once it has occurred is not as inherently safe as taking measures to reduce the likelihood of an incident occurring.
- Between these two extremes the report identified many other hybrid definitions which are linked to both prevention and to design. OTO 98 148 [16] reviewed 220 hazard management measures, and identified a trend where inherent avoidance is better than

procedural mitigation; however it was not possible to draw any conclusions regarding the relative merits of add-on active methods of avoidance and inherent control (Table 2.1).

Table 1 Principles of prevention (OTO 98 148 [16])

	Inherent	Add-on Passive	Add –on Active	Procedural
Avoid	Most Preferred		?	
Prevent				
Control	?			
Mitigate				Least Preferred

The hazard management measures were categorised under sub-topics, corresponding to various stages in the life cycle of the installation, as shown in Table 2.2. The Table helps to place the fire and gas hazards (and corresponding hazard management measurement methods) in the broader context of management of all hazards.

Table 2 Hazard management measures, for a variety of hazards

Applied in design	Installation and operation	Other
• Robust and redundant design • Layout and separation • Design for blast pressure • Use of appropriate design standards and work practices • Use of competent design engineers / contractors • Reduce manning • Reduce hazard • Reduce offshore activity • Design for people • Design for weather tolerance • Design for seismic activity • Passive fire protection	• Procedural measures to avoid ship collision • Fire and gas detection and fighting systems • Devices to prevent dropped objects and collisions • Procedural controls • Inspection methods and philosophies • Cathodic protection • Floating vessels	• Control of modifications • Emergency measures

Tables 2.3 and 2.4 show the explosion and fire hazard reduction measures respectively, originally reported in OTO 98 148 [16] in sequential order, classified according to life cycle stage and type of measure.

Table 3 Hazard reduction measure for explosion

Stage	Description
FEED	Design for maximum pressure
Conceptual	Process and compress gas onshore to reduce processing risks offshore
Conceptual	Avoid high energy systems
Conceptual	Select less hazardous materials
Conceptual	Hold materials in a form, or under conditions, to render them non / less hazardous
Conceptual	Use less hazardous materials
Design	Improve layout of equipment and minimize congestion
FEED	Maximise ventilation including use of blow out panels
Conceptual	Build accommodation platform separate from production platform
Design	Minimise penetrations through blast walls, and provide seals where required to avoid transferring blast loading to penetrating services
Conceptual	Minimise inventory of combustible material
FEED	Select and design blast equipment to withstand blast pressure
FEED	Ensure adequate supply and maintenance of deluge systems
Conceptual	Promote permit to work culture
FEED	Reduce the number of flanges
FEED	Ensure critical pipelines do not rupture when subjected to blast induced pressure
FEED	Divide the inventory to reduce the amount with a potential to ignite
Design	Design blast walls for high over pressures
FEED	Separate personnel from process hazards
Conceptual	Include systems for flaring
Conceptual	Provide a Temporary Refuge (TR) on an adjacent bridge linked structure

Based on Table 2.3 and Table 2.4 and on an HSE sponsored study on explosion loading on topside equipments [6], and on a variety of other papers and studies, Table 2.5 provides fires and explosions hazard reduction measures, specifically for piping systems.

Table 4 Hazard measures for fire and heat

Stage	Description
FEED	Design and build structure to allow for Emergency and Evacuation response within endurance time fire
FEED	Reduce potential inventory of combustible material within the accommodations module
Operational	Promote permit to work culture , including restrictions on hot work such as welding and grinding
Operational	Prohibit the use of non essential hot and meltable material (e.g. aluminium ladders)
Operational	Provide procedures for checking seals on flanges
Operational	Provide systems to detect gas or smoke entering TR or accommodation
FEED	Design with fewer and better flanges
FEED	Provide walls to segregate areas
Design	Use isolation valves
Design	Use HVAC systems Ensure HVAC systems will shut down when necessary to prevent smoke, fire or gas being spread to places where could be at risk in an emergency
Design	Protect escape routes, muster areas and TR from smoke and heat
Design	Provide passive fire protection for non-redundant part of the structure
FEED	Select less hazardous materials
Design	Provide systems to detect uncontrolled release and accumulation of hazardous material before ignition occurs
Design	Provide fire protection and isolation valves
Design	Select materials for construction which are more tolerant to heat
FEED	Layout of major vessels and primary steelwork to be protected from potential ignition sources
FEED	Provide redundancy to structure such that it can survive fire damage to some parts
Operation	Carry out inspection to ensure correct application of PFP at commissioning
Design	Assume that in an emergency all active measure for fighting will fail
Design	Apply passive fire protection on walls
Operation	Provide a rapid response plan including clean up and boom vessels and dispersant chemicals
FEED	Provide water deluge, water fog, gaseous extinguishing systems, fire water to cool adjacent risers
FEED	Provide fire and gas detection systems and deluge systems
FEED	Design topsides to keep risers and ESD valves as far away as possible from topside processes
FEED	Upon detection of fire automatic platform shutdown should be carried out, to reduce amount of inventory which can burn
FEED	Segregation of hazards by separation or distancing
FEED	Select layout of lifeboat areas and position of boats to protect personnel from smoke
Operation	Provide dampers
Operation	Provide smoke hoods
Design	Provide HVAC inlets on back face of TR to draw in fresh air (dependent on wind conditions)
Operation	Provide detectors that are based on rate of increase of heat produced, which provide fewer false alarms than traditional detection systems
Operation	Provide infra red detectors for detection of heat

Table 5 Fire and Explosion Hazard reduction measures for piping

Stage	Description
Conceptual Phase	
Minimise inventory of combustible material	
Process and compress gas onshore to reduce processing risks offshore	
Avoid high energy systems	
Select less hazardous materials	
Hold materials in a form, or under conditions, to render them non / less hazardous	
Use less hazardous materials	
Include systems for flaring	
Provide a TR on an adjacent bridge linked structure	
Promote permit to work culture	
Build accommodation platform separate from production platform	
Separate personnel from process hazards	
Improved means of escape	
FEED Phase	
Maximise ventilation including use of blow out panels	
Optimise deck height and equipment density	
Select and design blast equipment to withstand blast pressure	
Ensure adequate supply and maintenance of deluge systems	
Divide the inventory to reduce the amount with a potential to ignite	
Reduce the number of flanges	
Design for maximum pressure	
Ensure critical pipelines do not rupture when subjected to blast induced pressure	
Increase flange rating for critical piping	
Use welding rather than bolts	
Adopt pipe routes that will avoid drag loads	
Adopt pipe routes that will avoid large differential displacement between supports	
Adopt pipe routes with shielding and running behind beams	
Adopt pipe routes avoiding vent areas	
Optimise location and level of piperacks	
Optimise blast and fire protection (blast and fire walls)	
Design Phase	
Improve layout of equipment and minimize congestion	
Design blast walls for high over pressures	
Minimise penetrations through blast walls, and provide seals where required to avoid transferring blast loading to penetrating services	
Deluge system feeders and their manual bypass lines should be protected by providing PFP cladding or coating to piping and where necessary to supports, or by extended deluge cover. Specifically relevant to deluge feeders and bypass lines that skirt the separator area.	
Main blowdown header to be protected from fire in high hazard areas. Specifically relevant to header in vicinity of gas export metering package	
All Emergency shutdown valves which are recognised to be critical in isolating major inventories will satisfy fail to safe condition	
Optimise equipment fixings and piping supports	
Construction Phase	
Provide and incorporate quality assurance of construction of piping and piping flanges and supports into overall safety management system	
Reduce as much as possible welding on site	
Operational Phase	
Permit to work culture	
Provide operational training for all critical tasks and incorporate within safety management system	
Provide regular maintenance and inspection and incorporate within safety management system	

2.2.6 Interaction between fire and explosion hazard reduction measures for piping systems

The nature of interaction between explosion and fire will depend on whether an explosion precedes a fire or whether it occurs during a fire. Issues to be considered include:

- Effect of explosion on active systems which require an action to be taken before the system can become effective. A common form of an active system is the firewater deluge system, which comprises a firewater main that distributes seawater to a network of small diameter pipes and nozzles, with valves controlling the flow of water. Therefore, the fire water main should be designed and assessed for its ability to resist explosion loading, drag wind and differential support movement.
- Effect of explosions on passive systems that do not require external activation to become effective. Such systems include cement based coatings, firewalls, Intumescents, etc… Such systems limit the temperature rise of underlying material by providing insulation or absorbing heat. Issues to be considered include strain compatibility and bonding of passive fire protection.
- Effect of fires on explosion resistance. For explosion occurring during a fire, the effect of fire on the explosion resistance can be significant as yield strength and Young’s modulus are reduced at elevated temperature. These should be taken into account especially as explosion resistant design involves utilising the ductility and plastic deformation capacity of members , which may be diminished under fire.
- Safety conflicts, where different safety consideration for fires and explosions are contradictory and where some ‘trading’ of benefits is necessary. Since most fatalities usually occur due to smoke inhalation under fire conditions, fire considerations usually overpower explosion safety considerations. Some common conflicts are presented in the table below:

Table 6 Safety conflicts between fire and explosion considerations

Conflict	Description
Segregation versus openness	Segregation of a platform using solid fire walls could result in an increase in overpressure when an explosion occurs
Ventilation versus weather protection	Ventilation is desirable because it reduces overpressure due to explosions, however it can lead to the spread of smoke due to fires.
Deluge versus ignition	If the deluge system is to be triggered on gas detection, care should be taken not to contribute to probability of ignition

2.2.7 New versus existing installations

The safety management plan stipulates that the safety of an installation should be continuously reviewed during its operational life. However, in addition to the above requirement, it may be necessary top re-assess the installations safety against fires and explosions, for a variety of reasons, including:

- New information which alters the consequence or likelihood category (and therefore the risk level) of the installation
- Modification to the purpose of the installation, e.g. introduction of extended drilling
- Changes to the regulatory regime

Once the need to reassess an installations safety is identified, a risk assessment study is carried out depending on the principle of proportionality. Assuming that a need for risk reduction measures has been identified, it is important to be aware of the limitations of risk reduction measures at the operational stage as compared to the conceptual design stage. Figures 2.7 and 2.8 [20] show the increasing importance of control and mitigation measures (as opposed to elimination and prevention) during the operation stage of the installations life cycle (as opposed to the conceptual and feed stages in an installations life cycle).

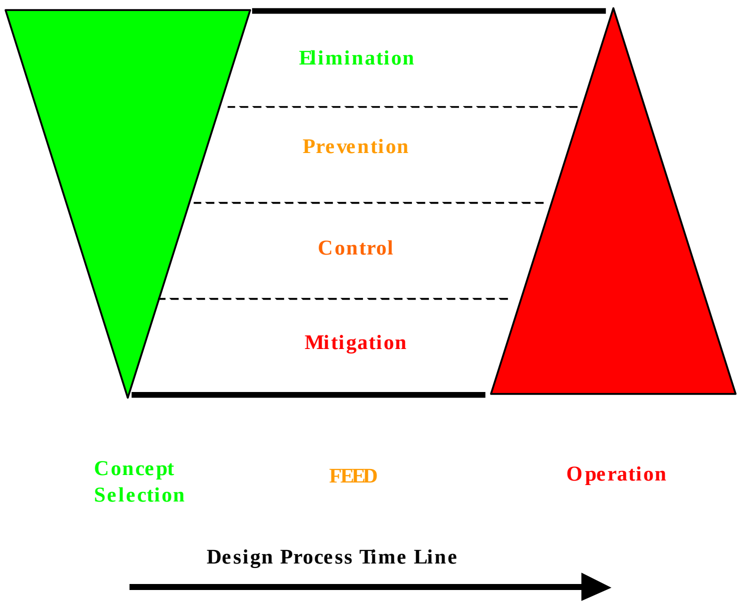


Figure 7 Opportunity to Modify hazards at the operation stage

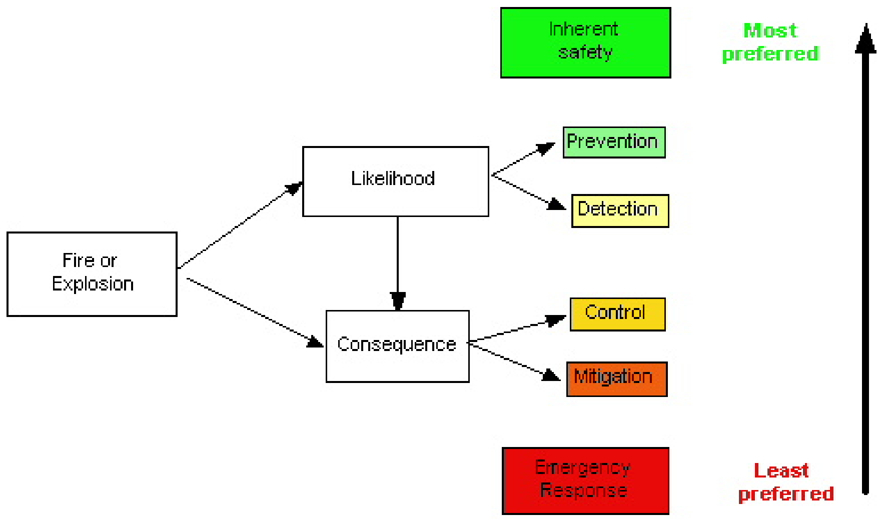


Figure 8 Reduction measures at various stages in an installations life cycle

2.3 RISK ASSESSMENT

An important concept in the determination of the loading acting on piping systems, and in determining the response of the piping system to explosion loading is the principle of proportionality, as specified in the HSE guide to the Offshore Installations (Safety Case) Regulations - 1992 [21] and the HSE Guidance on 'As Low as Reasonably practicable (ALARP) decisions in control of Major accident hazards (COMAH) [22].

Proportionality must be considered in at least two aspects of the safety assessment:

- The robustness of the risk assessment used, and
- The depth of the ALARP demonstration
- It may also be appropriate when considering the concept of gross disproportion when assessing the adequacy of the ALARP demonstration

The HSE guidance for the COMAH safety report states that the depth of the analysis in the operators risk assessment should be proportionate to the scale and nature of the major accident hazards presented by the establishment and the installations and activities of it. The depth of analysis that needs to be present depends on the level of risk predicted before any additional risk reduction measures are applied. The nearer the risk to the intolerable boundary, the greater the depth of analysis. There are various kinds of risk assessment that may be used depending on proportionality. These range from qualitative at the lowest level, through semi-quantitative up to quantitative at the highest level, as illustrated in Figure 2.9 below.

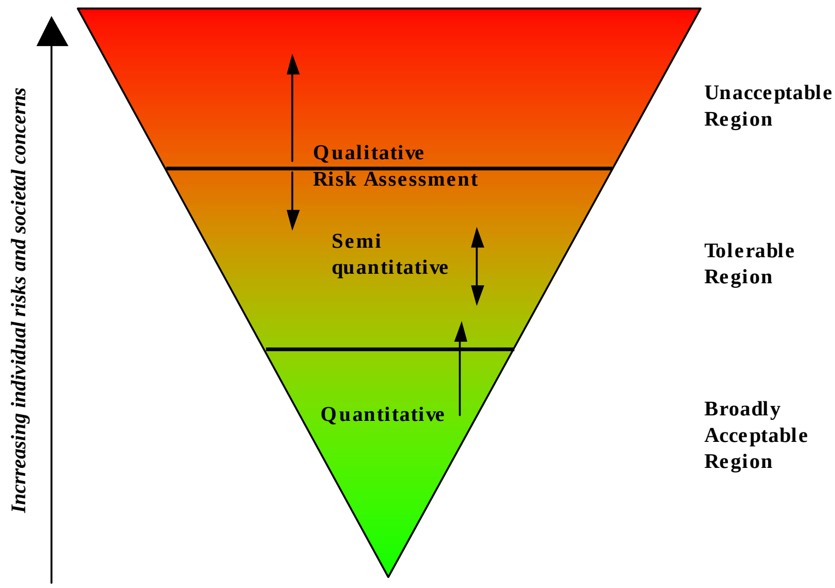


Figure 9 Types of risk assessment

A similar approach is put forward in the FABIG Technical Meeting on Safety Case Preparations, The Industry Responds [23] where in one of the presentations the following risk matrix is used to determine the level of assessment required. However, it should be recognised that it is not possible to make a direct correlation between the risk categories in Table 2.7 below and the risk regions in the figure above.

Table 7 Risk matrix 1, as a function of consequence and frequency

Frequency / Consequence	Extremely improbable[1]	Extremely remote[2]	Remote[3]	Probable[4]
Minor[5]				
Severe[6]				
Major[7]				
Catastrophic[8]				

Notes:
1. Not anticipated in operational life of all similar installations
2. Unlikely in total life of all possible installations, but nevertheless possible
3. May occur in the total life of a number of similar installations
4. May occur once or more in the life of a single installation
5. Does not significantly reduce the installations safety
6. Potential for adverse effects on occupants but continued safe operation not at risk
7. Continued safe operations is severely at risk
8. continued safe operation ceases to be possible
9. Green: No further assessment required
10. Orange: Further assessment required
11. Red: Further assessment with QRA required

Another approach is to have a risk matrix with three frequency and three consequence categories as shown in Table 2.8 below. This seems to be the risk matrix adopted by most of the codes.

Table 8 Risk Matrix 2 as a function of frequency and consequence

Consequence \ Frequency	Low	Medium	High
Low	Low	Low	Medium
Medium	Low	Medium	High
High	Medium	High	High

In view of the above discussion on the principle of proportionality in risk assessment, it becomes important to view the criticality of piping systems with the global context of other critical system on the installation. Figure 2.10 below [24] shows the explosion and fire criticality, for various components on the installation.

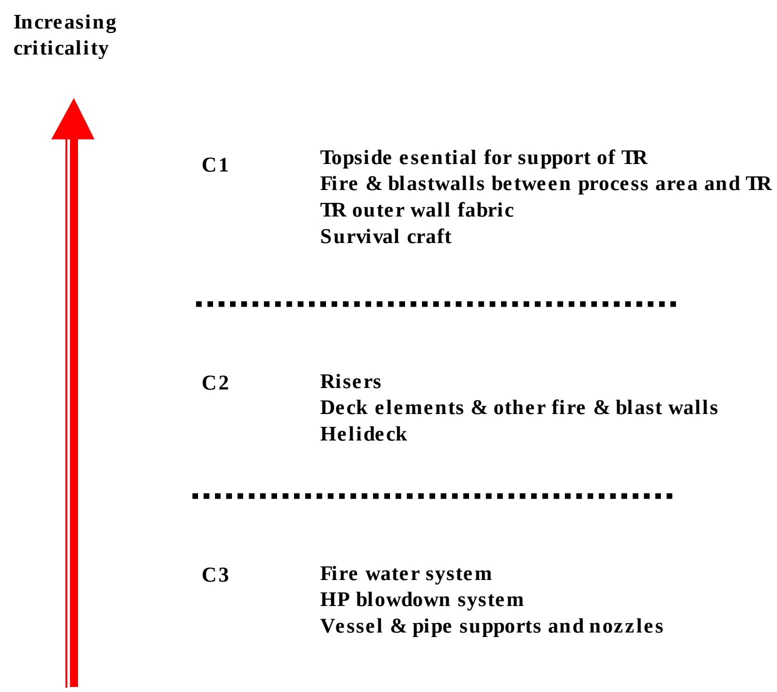


Figure 10 Fire & Explosion Criticality

It can be seen from the above discussion that regardless of the method used to arrive at the level of risk, the depth of the risk assessment process is proportional to the level of risk. Figure 2.11 shows how the risk assessment process fits within the overall hazard management process.

The level of risk assessment can be determined from Figure 2.12 using the following steps:

- Determine frequency and likelihood of event
- Determine the risk picture (low, medium and/or high level risk)
- Select level of risk analysis to be proportionate to level of risk.
- Note that for medium level risk, either low level or high level risk assessment will be carried out.

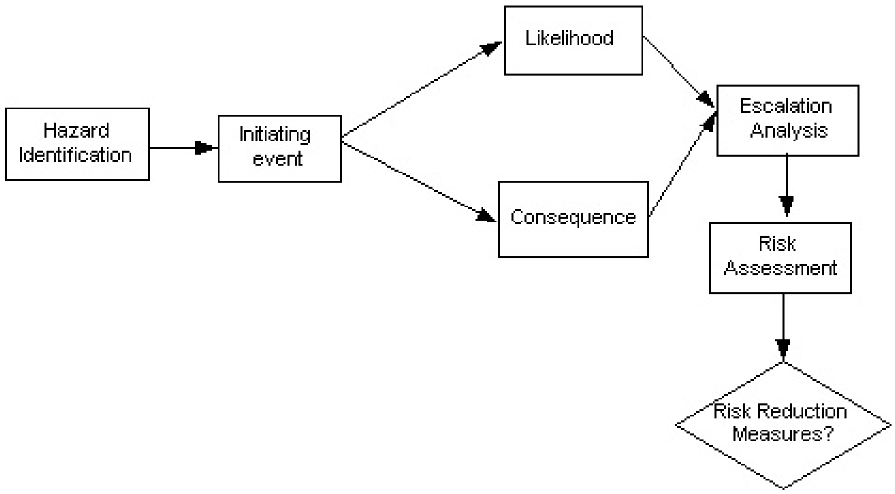


Figure 11 Risk Assessment within the overall hazard management process [20]

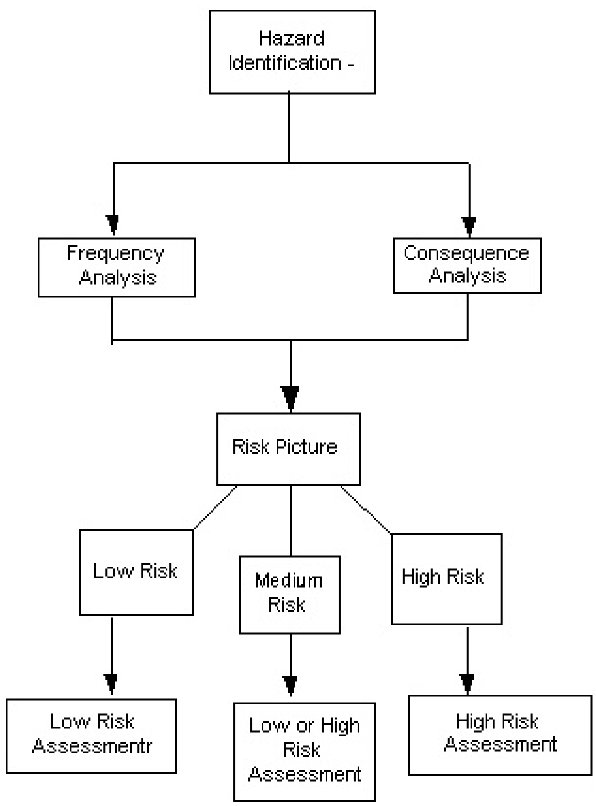


Figure 12 Process for selection of level of risk assessment []

Figure 2.13 [25 and 26] shows how the three risk levels (and the corresponding level of risk assessment) would fit in the ALARP Triangle and boundaries. In case of medium risk level which is closer to the L3 region, a high level risk assessment would be carried out. In case of a risk level closer to the L1 region, a low level risk assessment would be carried out.

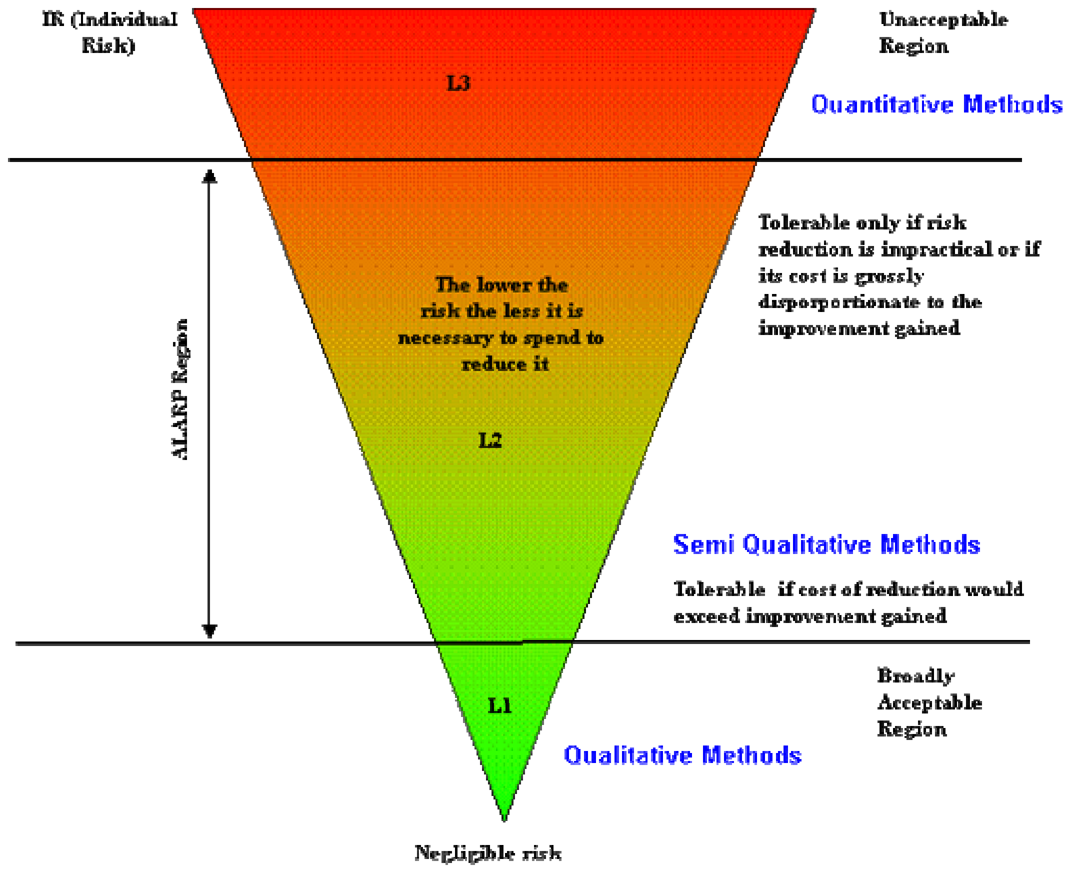


Figure 13 Level of Risk on ALARP Boundaries [25 and 26]

Figures 2.14 and 2.15 show the process for low risk assessments for explosions and fires respectively, while Figure 2.16 shows the process for high level risk assessment against fire and explosions loading.

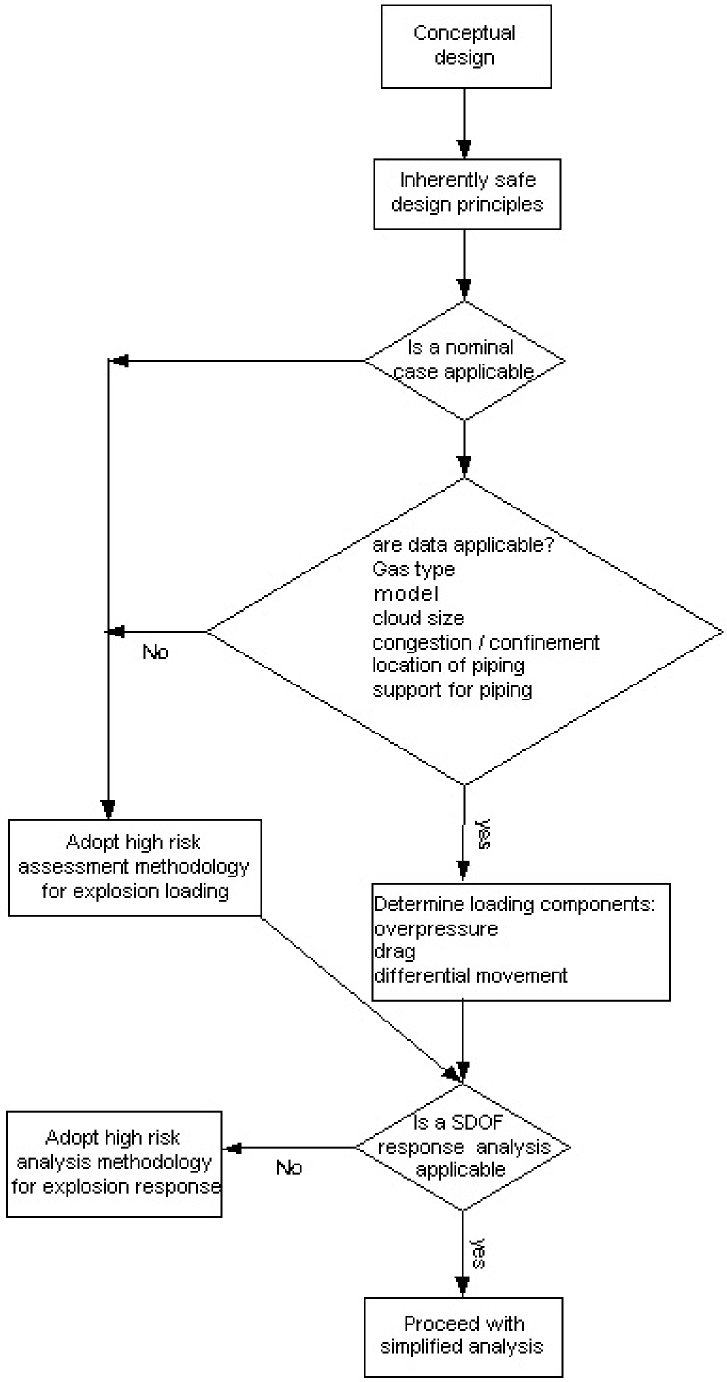


Figure 14 Low level explosion risk assessment process

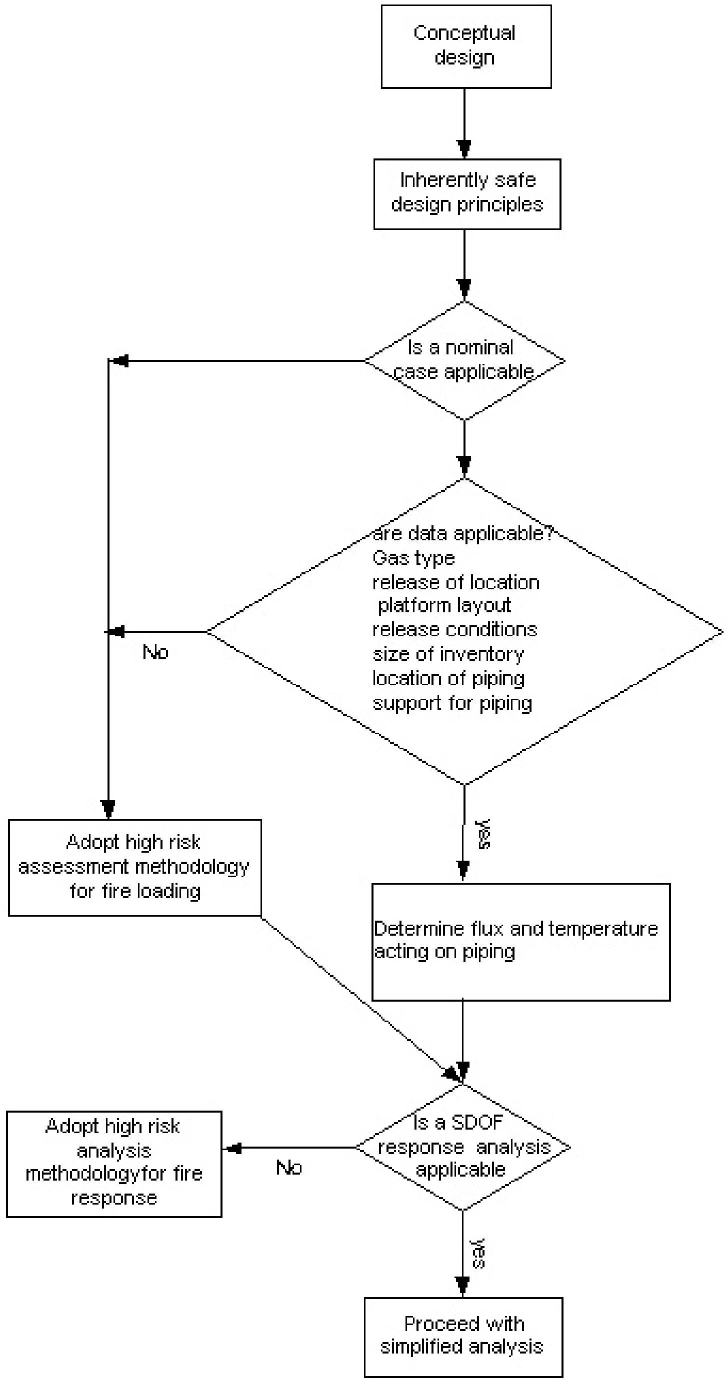


Figure 15 Low level fire risk assessment process

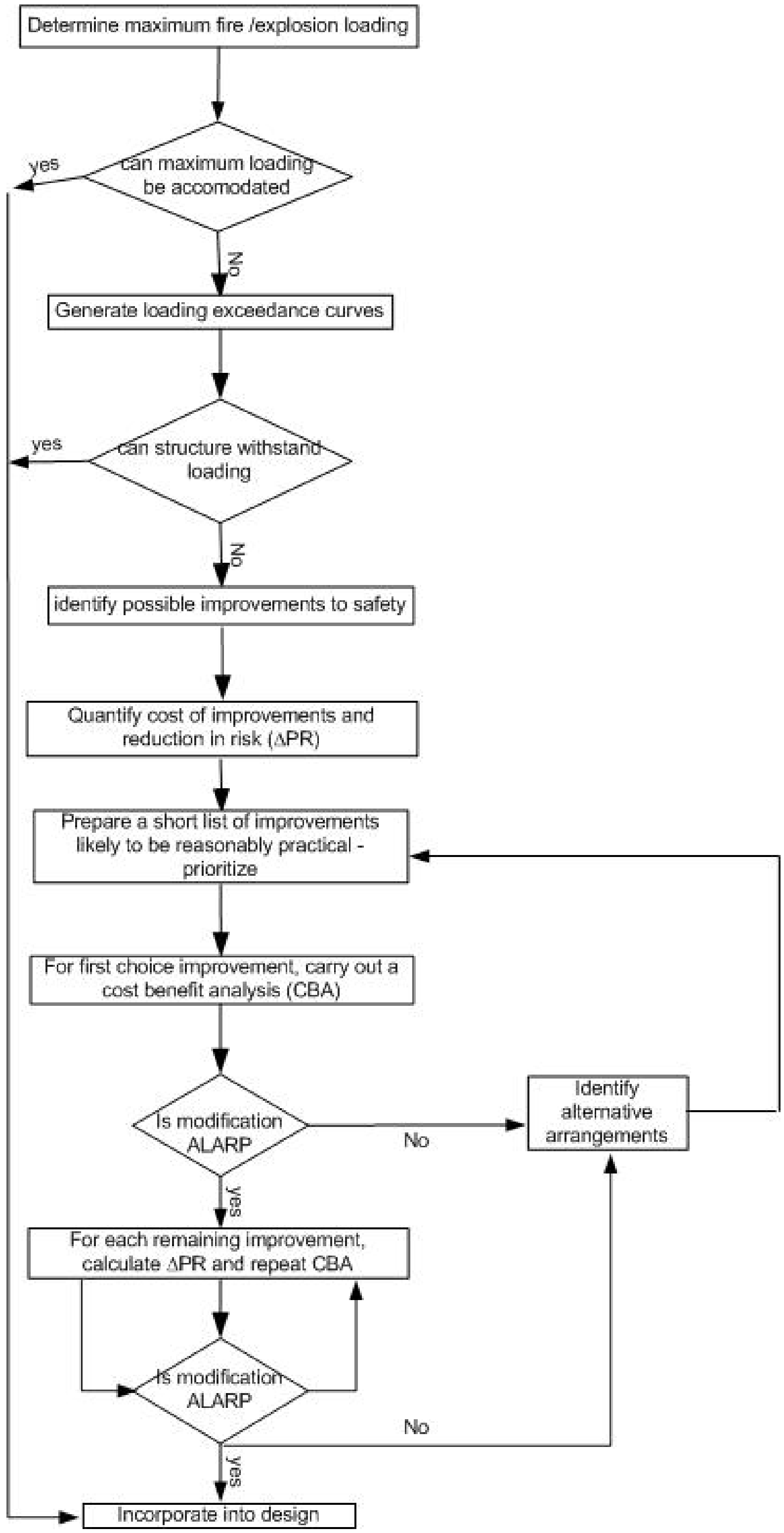


Figure 16 High level fire and explosion risk assessment process

The risk assessment process can be subdivided into:

- Determining the explosion loading
- Determining the fire loading
- Determining the explosion response
- Determining the fire response
- Determining the explosion and fire response

Qualitative, semi-quantitative and quantitative methods (see Figure 2.9) for achieving the above steps are briefly discussed below, while a more detailed discussion may be found in the forthcoming chapters.

Methods used for determining the explosion loading

Qualitative methods for determining the explosion loading on piping systems should account for drag and overpressure components of the loading. The differential displacement at the piping supports is also considered a loading acting on the piping system even if it is a *response-effect* of the topside structure.

Qualitative methods include nominal values of overpressure based on various parameters affecting the explosion and drag (such as ventilation, congestion, layout, etc…).

Semi-quantitative methods include phenomenological models that attempt to model, albeit in an approximate way the underlying important physical processes involved in an explosion.

Quantitative methods are numerical methods that solve the underlying equations describing gas flow, turbulence and combustion processes – examples include FLACS [27], AUTOREARGAS [28] and EXISM[29].

Methods used for determining the fire loading

Methods for determining the fire loading on piping systems should be able to provide an estimate of the temperatures that the piping system will be subjected to.

Qualitative methods provide nominal temperature values depending on various parameters such as fuel type, location, release conditions quantity of release.

Semi-quantitative methods, such as phenomenological, often approximate one dimensional, models that describe time averaged fluid flow coupled with sub-models describing turbulence, combustion processes and flame radiation

Quantitative models consist of the main framework of equations that describe time averaged fluid flow coupled with sub models that may be empirical describing turbulence, combustion processes and flame radiation.

Methods used for determining the explosion response

Selecting an appropriate method for the analysis of the response of piping systems subjected to explosions, is dependent on several factors including:

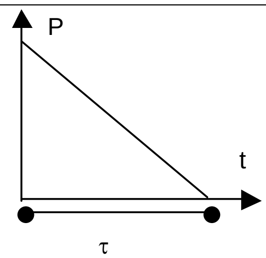
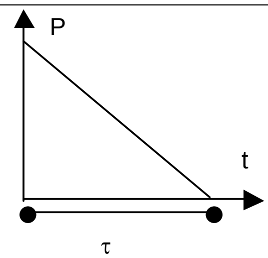
- Loading regime (relative period of loading to period of piping)
- Coupling of piping/topside response (relative period of piping to period of topside structure)

* Validity of superposition principles

Loading Regime

The interim Guidance Notes [2] defined different loading regimes based on the duration of the loading as compared to the natural period of the structures. The boundaries of these loading regimes were then revised by the Norsok Standard N- 004 Design of Steel Structures – Annex A [30], and are reproduced below:

Table 9 Effect of loading Regime on treatment of overpressure component of loading

<table>
<tr><td>Loading regime
Parameter</td><td>Impulsive (short)
$\tau/T < 0.4$</td><td>Dynamic (intermediate)
$0.4 < \tau/T < 3.0$</td><td>Quasi-static (long)
$\tau/T > 3.0$</td></tr>
<tr><td>Peak Value</td><td>Preserving exact peak not critical</td><td colspan="2">Increase or decrease in peak will result in a similar trend in the response</td></tr>
<tr><td>Duration</td><td>Preserving exact duration not critical</td><td>Slight changes in duration may affect response</td><td>Duration more important as response becomes plastic</td></tr>
<tr><td>Impulse</td><td>Accurate representation of impulse important. Negative impulse may be important</td><td>Accurate representation of total and rise times important</td><td>Accurate representation of impulse not important</td></tr>
<tr><td>Rise Time</td><td>Preserving rise time not critical</td><td colspan="2">Preserving rise time very important.</td></tr>
<tr><td>Idealised pressure time</td><td></td><td colspan="2"></td></tr>
<tr><td>Analysis method</td><td>Energy methods</td><td>SDOF / MDOF</td><td>Static / Energy Methods</td></tr>
<tr><td colspan="4">Notes:
1. τ is duration of loading
2. T is natural period of piping system
3. t_r is rise time of loading</td></tr>
</table>

The loading on piping systems is composed of both drag and differential movement components in addition to the overpressure component. Currently, it is not clear how the loading regimes affect the treatment of the drag loading.

Coupling of Piping / Topside response

The nuclear code ASCE 4-98 [31] provides clear guidelines as to the criteria for selection of coupled/uncoupled analyses for items of equipment. ASCE 4-98 [31] recommends that coupled analysis is not required if the equipment (or secondary system) satisfies the following requirements:

- Total mass of component is 1% or less of supporting primary structure. If components are identical and located together, their masses shall be lumped together.
- Stiffness of component supported at two or more points does not restrict movement of primary system and
- Static constraints do not cause significant redistribution of load in primary structure.

For tanks and vessels with single deck attachment (i.e. connected at one deck level only and with no significant separation between the support points so that the acceleration at the various points can be assumed to be the same), the selection of coupled analysis or uncoupled analysis is based on the frequency ratio and the modal mass ratio. From the numerical values of the frequency ratio and modal mass ratio, the selection of the type of analysis can be carried out based on Figure 2.17 [31]:

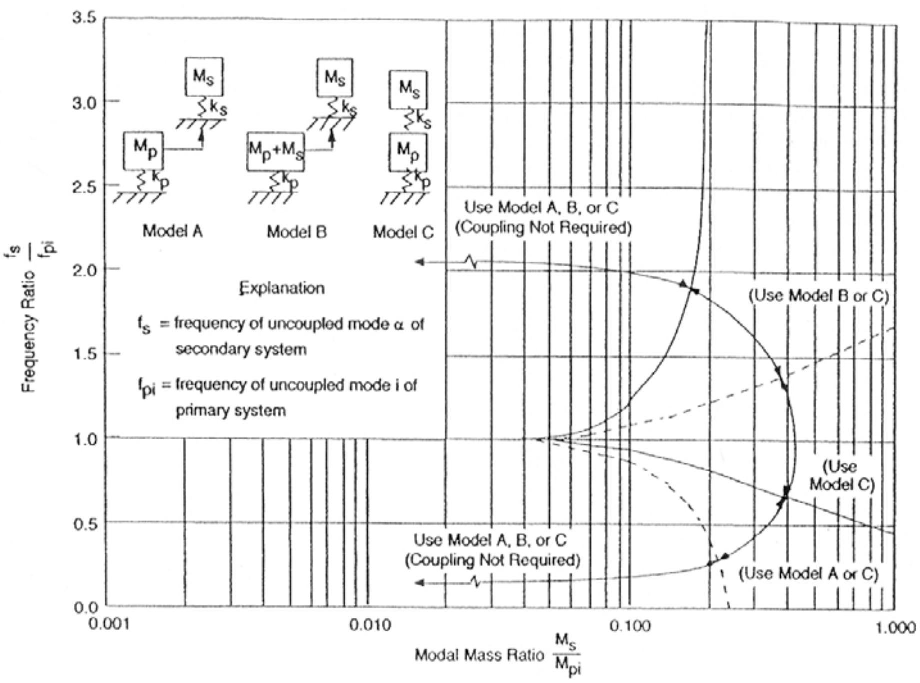


Figure 17 Selection of uncoupled versus coupled piping – topside analysis

Validity of superposition principles

If a SDOF method is to be used then the response due to drag, overpressure and differential will have to be determined separately and then summed using superposition principles. Even for small diameter piping where overpressure can be ignored, there may be two components of loading (drag combined with deck accelerations) in different directions and with different time variations. The applicability of SDOF methods in such cases becomes questionable. The situation becomes worse if one is to take plastic deformations into account; however, FABIG Technical Note 7 [32] provides a SDOF method which takes into account catenary effects. OTO 1999 046 [6] concludes that, in practice, the drag loading is largely confined to one direction and the problem in applying the SDOF method is reduced to how to combine a drag load in one direction with differential deck acceleration effects. The various methods for analysing the response of piping systems subjected to explosions are discussed in detail in Chapter 3.

Methods used for determining the fire response

The Interim Guidance Notes [2] reviews the following methods for response of piping to fire loading:

- Zone methods where the platform is divided into zones with predetermined design standards.
- Limiting temperature methods which assumes that structural failure occurs when the steel reaches a certain critical temperature.
- Code check methods based on the use of existing ambient temperature structural design codes, while incorporating reduced safety factors.
- Approximate analytical methods, where the hoop and longitudinal stresses are calculated by formulae provided in the ASME B31.3 code [33] and checked against acceptance criteria
- Simple non-linear analysis, this approach is best used for cases where linear elastic analyses indicate that only a few components will fail. It enables a more detailed assessment for consequence without resorting to fully non-linear analysis. It is based on modified code checks that are used to determine member utilisations.
- Advanced non-linear analysis that allow the fire duration of a piping system to be based on the resistance of each member. A progressive collapse study can be carried out via incremental temperature analysis.

All the above methods will be discussed in more detail in Chapter Four.

Methods used for determining the explosion and fire response

When considering the combined effect of fires and explosions, any combinations of analysis types is permissible depending on the level of risk for fires and explosions. It is possible to combine:

- A simplified treatment of explosions with a simplified treatment of fires;
- A simplified treatment of fires with an advanced treatment of explosions; or
- A simplified treatment of explosions with an advanced treatment of fires.
- An advanced treatment of fires with an advanced treatment of explosions.

2.4 BLAST AND FIRE STRATEGY FOR PIPING

As mentioned in the sections above, the safety management system will have a Health Safety and Environment (HS & E) plan, which will include a blast and fire strategy, which in turn will include a plan for blast and fire strategy for piping. This plan will be comprised of:

- Identifying safety critical piping
- Identifying responsibility of various disciplines and interaction between them
- Developing a design procedure for protection of piping against fires and explosions
- Developing a design procedure for the protection of piping supports against fires and explosions.
- Control and mitigation measures for the protection of piping and piping supports against fires and explosions.

2.4.1 Identifying safety critical piping

Critical piping systems that are to be addressed in respect of blast and fire are:

- Fire protection systems in process areas and utility areas.
- Export risers
- High-pressure flare system including the blowdown valves and piping from major hydrocarbon inventory vessels to blowdown valves.

2.4.2 Responsibilities and interaction between disciplines

The flow chart below shows the responsibilities of each discipline and the required interaction between disciplines at various stages in the platform life-cycle.

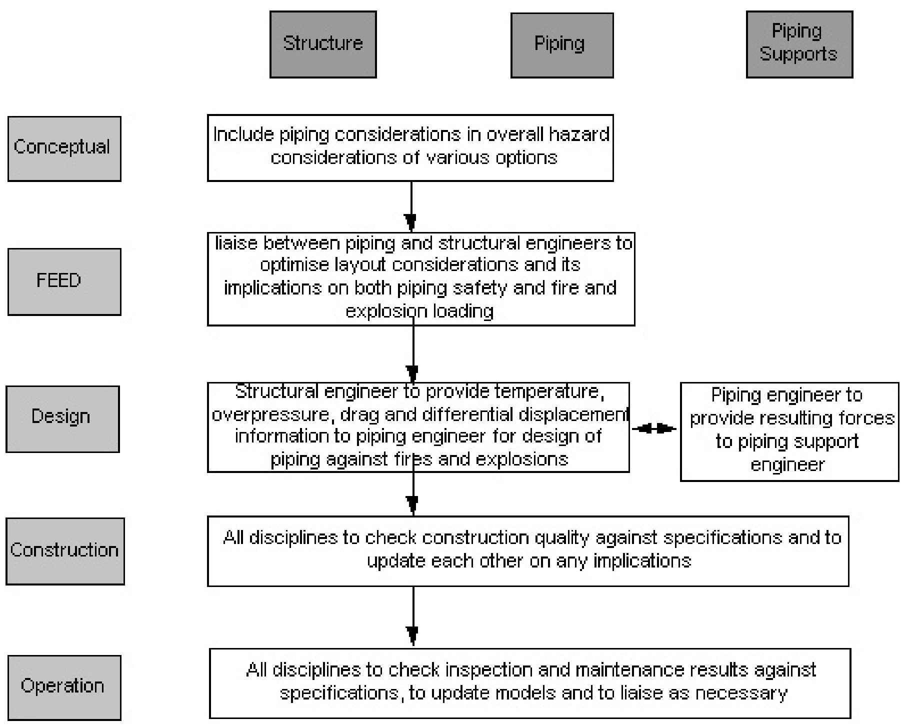


Figure 18 Responsibilities and interaction between disciplines at various stages of the life cycle

2.4.3 Procedure for protection of piping against fires and explosions

The flow chart below shows the procedure for piping design against fires and explosions.

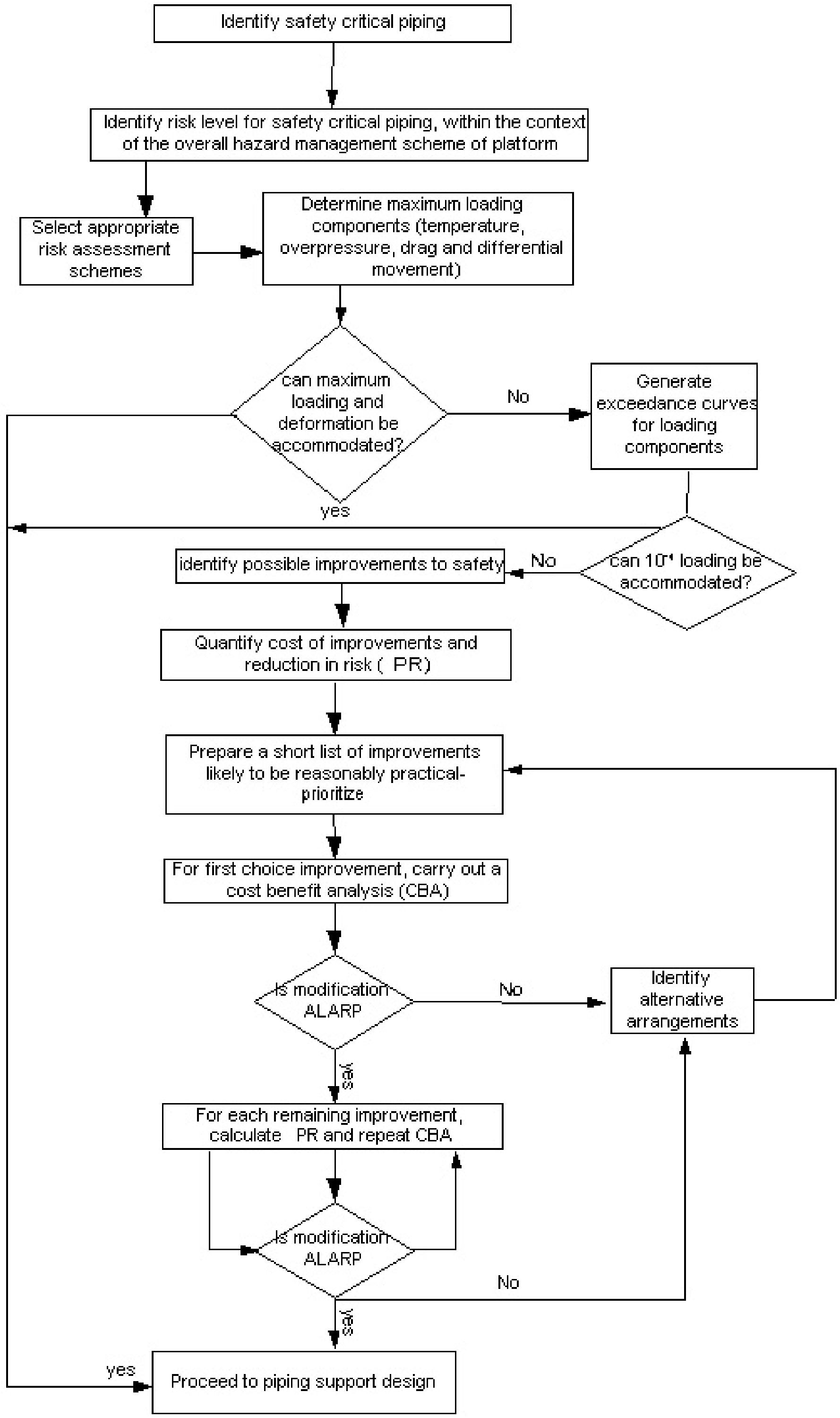


Figure 19 Procedure for protection of piping against fires and explosions

2.4.4 Protection of piping support against fires and explosions

The figure below shows the procedure for piping support design.

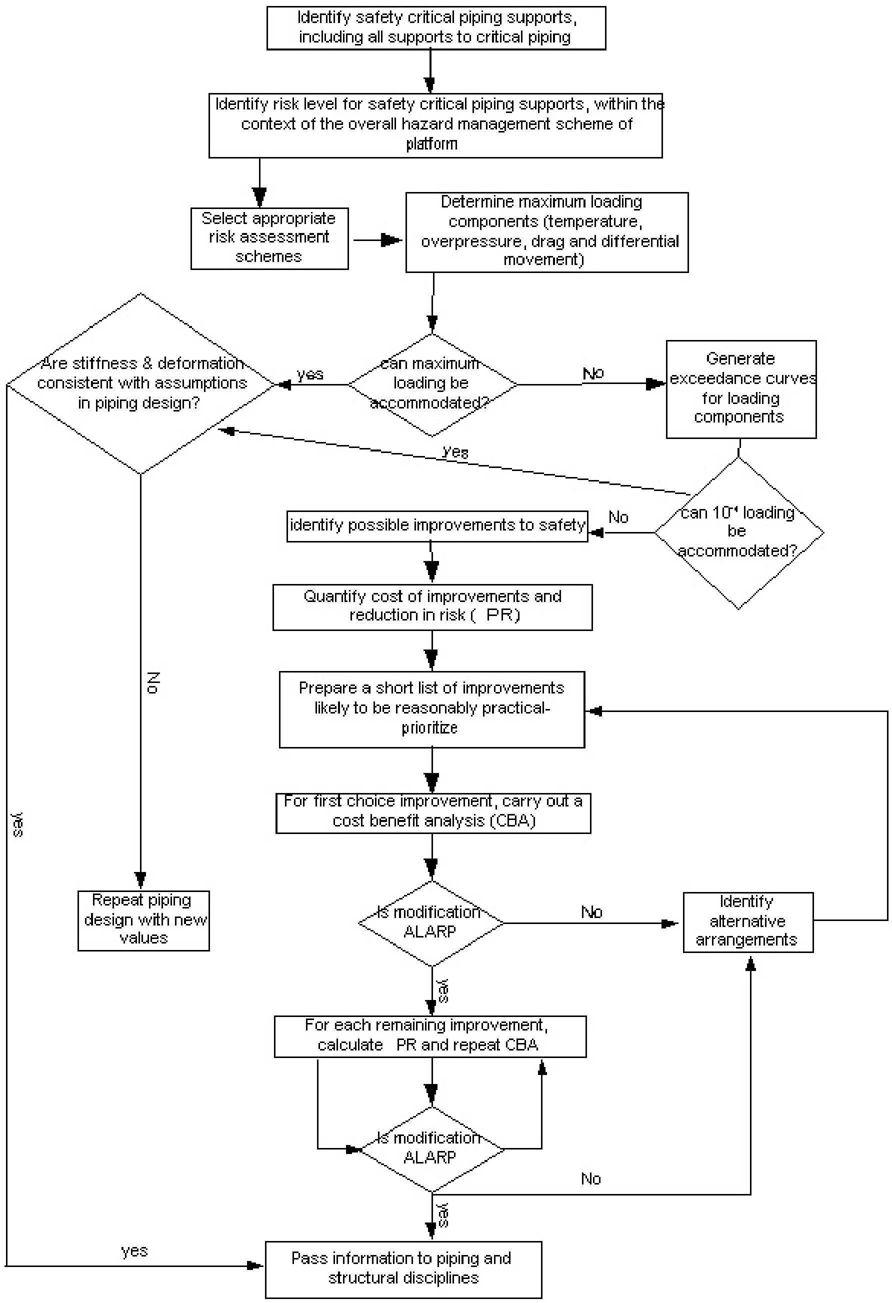


Figure 20 Piping support design against fires and explosions

2.4.5 Control & Mitigation measures for protection of piping and piping supports against fires and explosions

While it is encouraged to eliminate hazards at the conceptual stage, there will always be a residual hazard which should be controlled /mitigated against using control and mitigation systems. ISO 13702 [34] provides recommendations and guidelines for the control and mitigation of fires and explosions on offshore production installations. Passive rather than active control and mitigation systems are always to be preferred. Typical control and mitigation systems are listed below:

- Installation layout
- Emergency shutdown system and blowdown
- Control of ignition
- Control of spills
- Emergency power systems
- Fire and gas systems
- Active fire protection
- Passive fire protection
- Explosion mitigation and protection systems
- Evacuation escape and rescue

3 DESIGN OF PIPING AGAINST EXPLOSIONS

3.1 INTRODUCTION

This chapter considers the techniques that may be used to determine blast loads and their effects on the structure. Section 3.2 presents a discussion on the interaction of the piping discipline with other disciplines. Section 3.3 presents a review of the basic loading types acting on piping due to explosions. It also reviews the available methods for determining the magnitude of blast loads for use in design. Section 3.4 presents the types of piping used offshore, and summarises their relevant material properties. Section 3.5 presents a discussion and methodology for determining the effects of blast loading on piping systems. Both advanced and simplified methods are presented. Section 3.6 discusses acceptance criteria and Section 3.7 provides guidelines for ductile construction. Finally, Section 3.8 addresses FPSO specific issues.

3.2 INTERACTION OF PIPING WITH OTHER DESIGN DISCIPLINES

One of the design goals is the prevention of escalation. Failure of a small pipe or vessel can lead to an escalation of an initial explosion event and the outbreak of fires, which in turn can lead to the failure of larger vessels and / or pipes, that may lead to more severe consequences as shown in Figure 21 [35]. The safety management systems discussed in the previous chapter provide barriers against such escalations. The proper design of piping systems to withstand explosions is one such barrier.

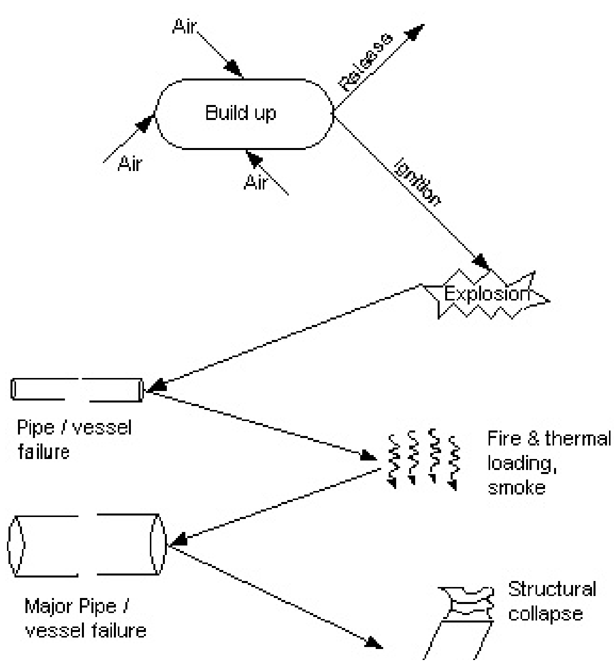


Figure 21 Effect of piping failure on potential for escalation

A typical offshore project will have a considerable number of pipework and pipework supports, of varying degrees of criticality. Figure 22 below shows the development of information for the design of piping and their supports as the project is progressed. It can be seen that the majority of safety critical piping and piping supports are approved for construction before the final data is available. Previous experience from existing platforms with similar functions and facilities provide a valuable tool in ensuring that the design based on intermediate data is acceptable.

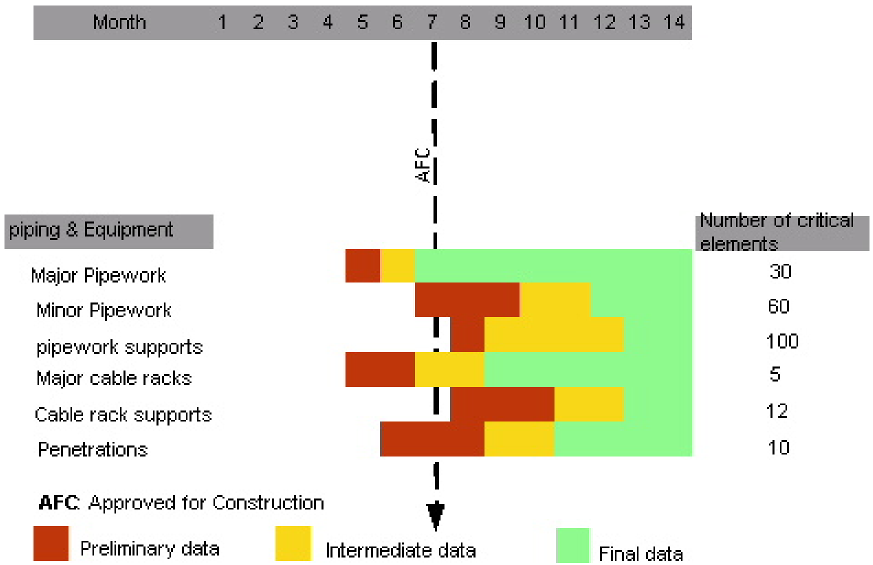


Figure 22 Typical Numbers of piping and equipment safety critical elements

3.2.2 Discipline Interaction

Piping design requires interaction and exchange of information with many other disciplines. Figure 23 shows the building and exchange of information between the piping, layout, safety and design disciplines, as a project is progressing [36, 37]. Initially large equipment and pipes, together with the preliminary structural layout, is used to build the topside CAD model, which in turn is used when generating the first explosion pressure analysis. The explosion loading is used for the first structural analysis and the equipment and piping design. The CAD model is updated based on the new structural layout, equipment and piping design, and a new explosion pressure analysis is carried out. Results from the second explosion pressure analysis are used to carry out a second structural response analysis and a further analysis on pipes and equipment. Results from the latter two are fed back into the CAD model to build the final CAD model. It should be noted that the pipe support stiffnesses used in the analyses may have a significant effect on the pipe stresses and therefore should be checked against assumed values.

In case insufficient data exists, artificial congestion may be used in the first two CAD models so that the first and second explosion pressures are not significantly underestimated in comparison with the final explosion pressure. Section 3.2.2 will discuss this in more detail.

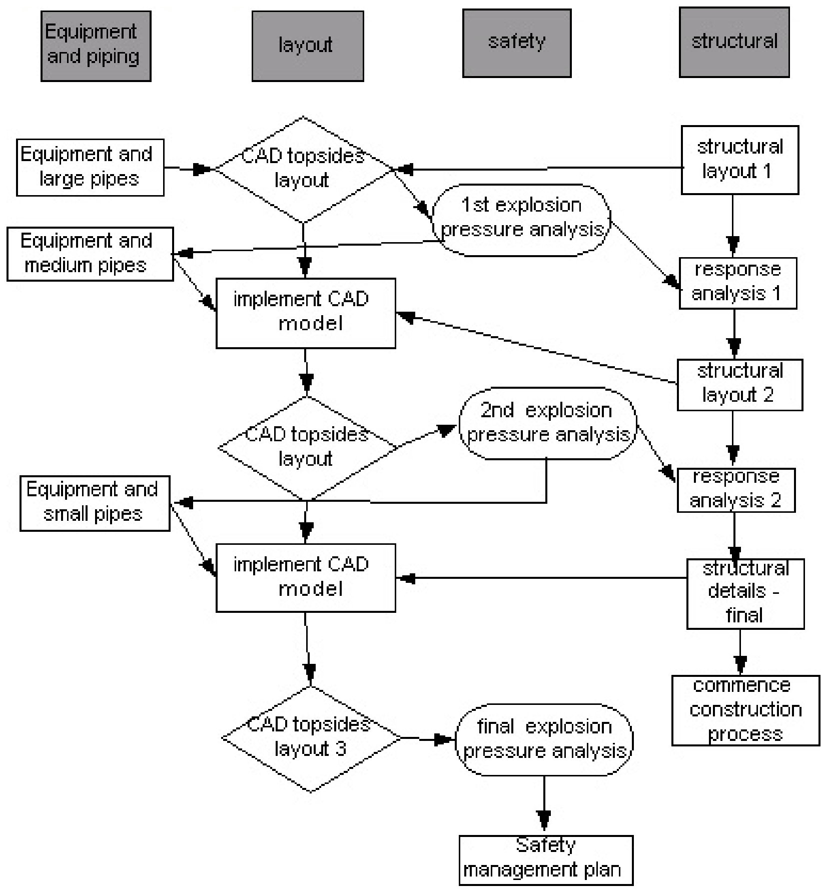


Figure 23 Interaction between piping and other disciplines

Figure 24 shows in more detail the equipment and piping design process using CAD software packages [36, 37]. Design milestones may be produced within the CAD software. Furthermore, process flow diagrams are being superseded by CAD information, which can be much more informative as it contains attributes such as pressure rating, material specification and insulation requirements.

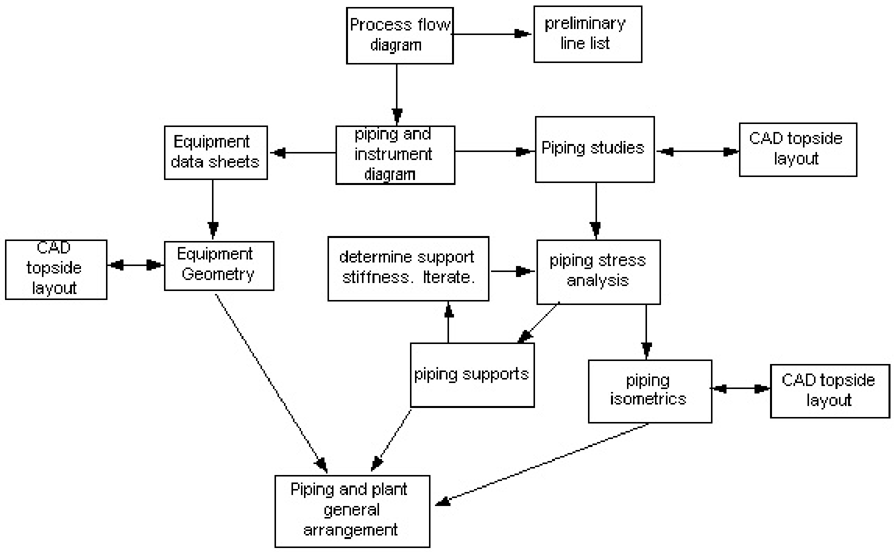


Figure 24 Development of the piping and equipment discipline

Figure 25, taken from OTO 1999 048 [36], shows a typical design schedule for a large new topside project from the pre-engineering stage to the construction stage. The progress of equipment, piping and structural design is shown with time. The boxes indicate points in time when an explosion analysis is carried out. Again, it can be seen that explosion analyses are carried out while the design of piping, equipment and structure is still underway. The piping design continues until the end of the project but the last opportunity to affect changes to the design and routing of major pipes would probably be around month 6 or 7, when results from the first explosion analysis are used to check the design of major piping before ordering them for delivery.

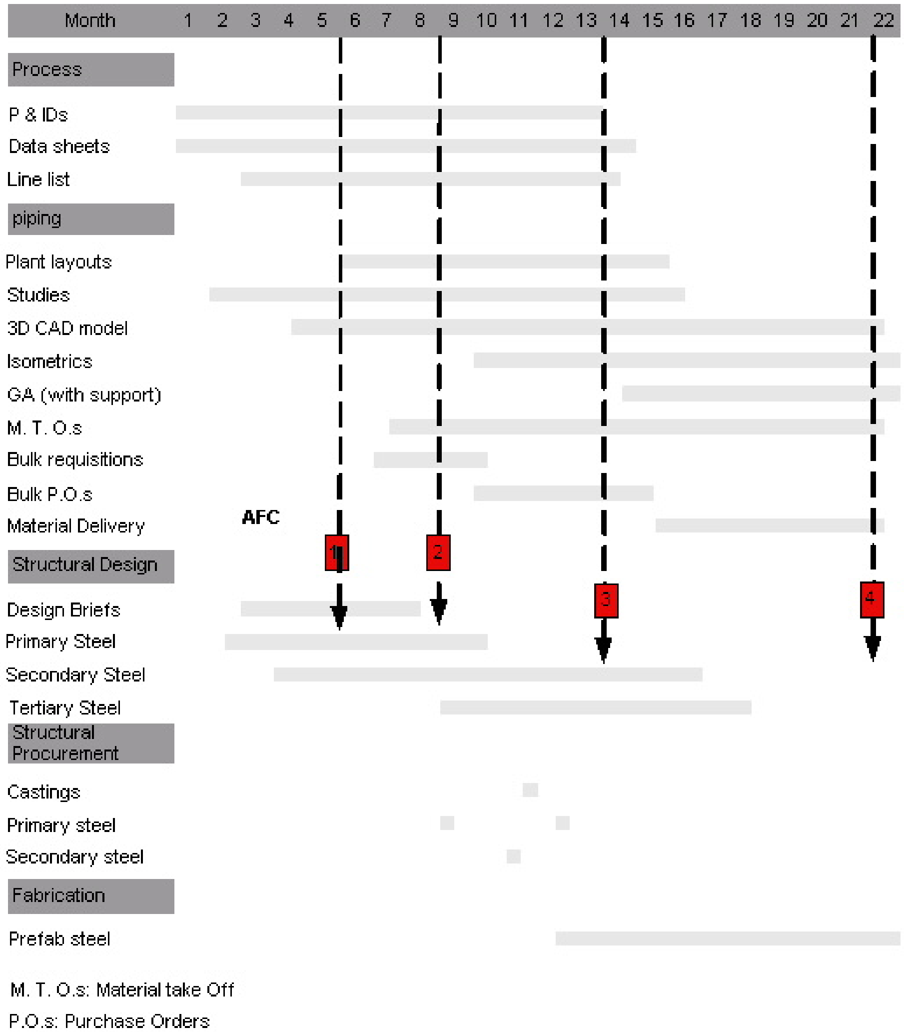


Figure 25 Typical project schedule

3.2.3 Overpressure estimation with progress of project

At the beginning of the project, very few details regarding the piping that will be used on the topsides are available. This is particularly true for the small and medium size piping that can significantly contribute to the degree of congestion, and hence the total overpressure developed due to an explosion event. Therefore, if the piping geometry is added to the CAD model only when the actual information becomes available, this may result in cases where the total final overpressure is several orders of magnitude larger than the overpressure that was used at the beginning of the project to design the structure and the major pipes and equipments. This can be seen in Figure 26 [36, 37]. Therefore to avoid such situations, where the overpressure is grossly underestimated at the beginning of the project, it is useful to introduce artificial piping and equipment congestion models. The proper use of such models can lead to initial estimates of overpressure very close to the final overpressure value, and thus avoid the need for re-assessment or strengthening.

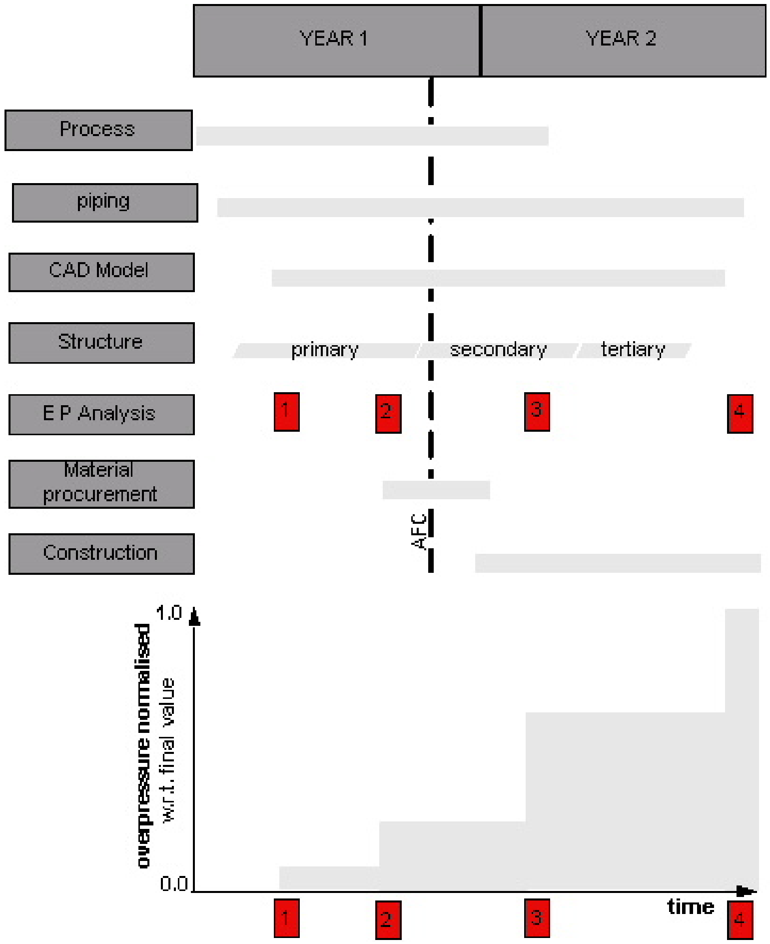


Figure 26 Growth of overpressure with project development

The weight control and material take-off disciplines play an important role in exchanging information with the layout discipline for building the CAD models (see Figure 27). The material take off (MTO) provides the estimating and ordering basis for all the material and equipment that will be used on the platform. For piping this information is usually broken down into the pipe specification together with sizes and corresponding approximate lengths. Items in the weight report that are approximate, and have not been technically defined, are usually defined as 'estimate to complete'. The weight control discipline uses the MTO to define the items to complete.

Based on this, OTO 1999 048 [36] concludes that a large amount of data is available at the early stages of projects. However, it also concludes that what is missing is an inter-disciplinary procedure that can represent all this information in a format amenable for use by the safety discipline engineers in determining the explosion pressure.

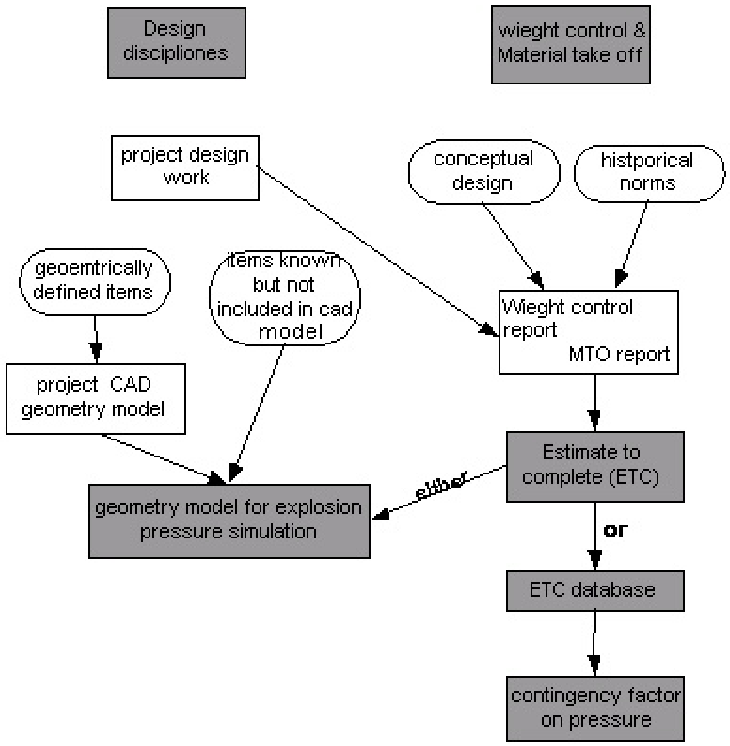
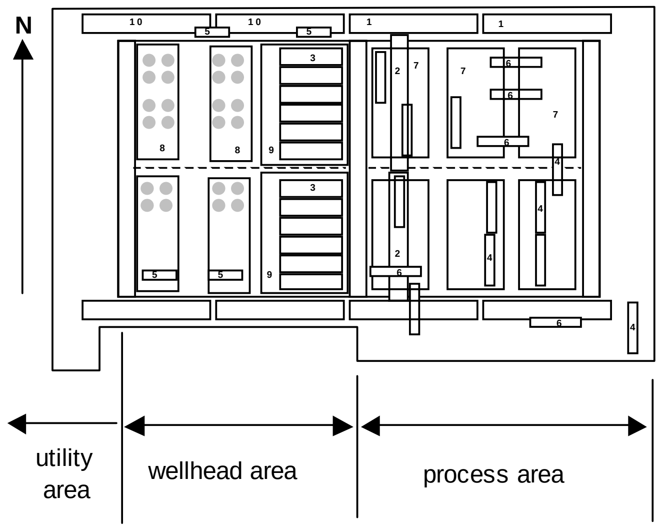


Figure 27 Development of geometry information with the progress of the project

The accurate assembly of artificial congestion models becomes possible as more and more platforms are built and considerable experience is gained. Such congestion models would vary according to platform size, type and function. One such congestion model, based on OTO 1999 048 [36], is shown in Figure 28

First the platform is divided into separate areas by function. Then for each area the need for main, secondary and tertiary pipe racks is identified, and estimates for pipe specification, sizes and length are provided. In this manner, it is possible to build artificial congestion models that are used to determine an accurate estimation of overpressure during the early stages of the project.



Block	Block Volume (m^3)	Number of bocks	Total Volume (m^3)	Function of Block
1	50	4	200	Main piperack in the process area
2	55	2	110	Transverse piperack
3	50	12	600	Manifold piping
4	20	11	220	Equipment piping (E-W)
5	17	4	68	Equipment piping (E-W), well head area
6	20	5	100	Equipment piping (N-S)
7	104	6	624	Secondary under-deck piping in the process area
8	80	4	320	Secondary under-deck piping in the well head area
9	120	2	240	Secondary under-deck piping in the manifold area
10	50	4	200	Main piperack in well head area
TOTAL			**2682**	

Figure 28 Typical Congestion in an Offshore Module

3.3 LOADING COMPONENTS ACTING ON PIPING DUE TO EXPLOSIONS

Two types of loading that must be considered in the design of piping systems due to explosions are:

- Overpressure
- Drag

Overpressure calculation has been discussed in detail in many publications. As far as piping is concerned, it is important to establish whether the calculation method will account for both overpressure and drag, or whether drag loading will have to be determined separately.

All of the most important components of drag and overpressure loading are accounted for in the Computational Fluid Dynamics (CFD) models. The analyst has the option to report drag impulses (which only accounts for form drag) or drag force by the direct load measurement (DLM) method, which accounts for the other drag load elements.

Design loads for small obstacles (diameter < 0.3m) may be computed using the drag impulse method. Values for large obstacles should be computed using the direct load measurement method, which takes into account the other drag load components. These other force components are small and out of phase with the form drag component when diameter < 0.3m. However, they can become significant when small diameter components are in close proximity.

In addition to drag and overpressure loading, a third component consisting of differential displacement at the piping supports should be accounted for. Figure 29 shows a segment of a typical high pressure piping collection system. It can be seen that the piping is restrained along various points of its length against movement in the x-, y- or z- direction. These restraints, if they are in the form of attachments to the main structure, may impose a differential displacement on segments of the piping system spanning between two such restraints. Determining the amount of differential displacement at the piping supports requires an accurate estimation of the support stiffness and may include a degree of iteration as more information becomes available as the project progresses.

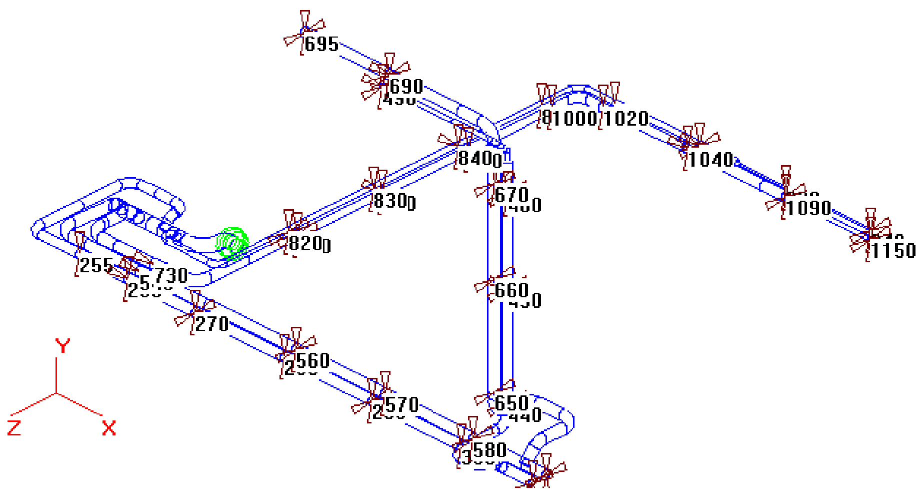


Figure 29 Segment of a typical HP system

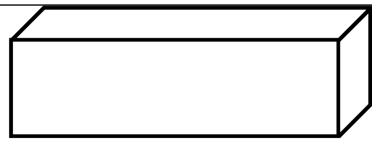
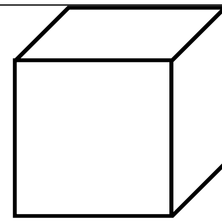
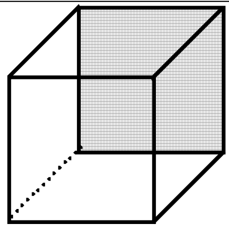
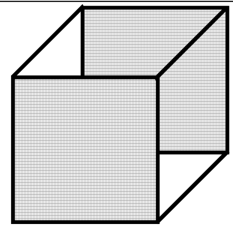
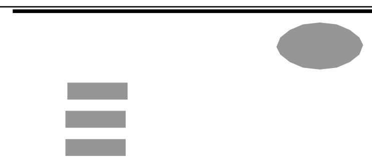
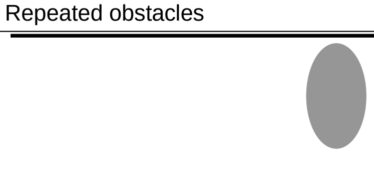
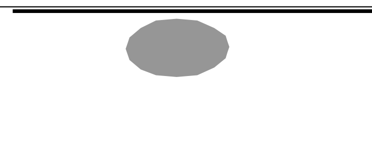
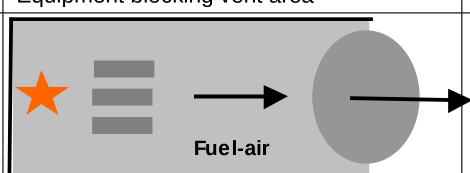
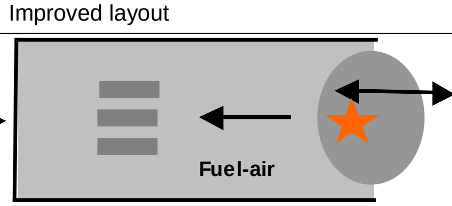
3.3.2 Parameters affecting explosion loading

The parameters affecting explosion loading are [2, 4, 5]:

- Shape of module where explosion takes place
- Degree of ventilation
- Degree of congestion and
- Ignition location

Modules closer to the shape of a cube are better than those closer to the shape of a rectangle, with one or more sides significantly bigger than the others (see **Error! Reference source not found.**). This is because the further a flame has to travel before it reaches open air, the more it will increase in strength. Ventilation on one side or on two adjacent sides is not as effective as ventilation on two opposite sides (this, again, would decrease the maximum distance a flame can travel before reaching open air). The degree of congestion will affect the build-up of overpressure. The more a module is congested, the more turbulence the flame is likely to undergo as it travels towards the exit, and therefore the higher the generated loading. The orientation of the obstacles can also play a significant part in increasing or controlling the loading. Obstacles arranged in series in the path of flame propagation will have a more detrimental effect on the loading. In addition, obstacles blocking part of the vent location will also lead to an increase in the loading. Location of ignition relative to the vent is also very important; the nearer the ignition location is to the vent, the less distance the flame has to travel, and the less the loading. These have all been discussed in greater detail in explosion handbooks.

Table 10 Effect of various parameters on explosion loading

Parameter	Bad	Good
Shape	 L>> W or L>>H	 L = W = H
Ventilation - cube	 One side or two adjacent sides	 Two opposite sides
Ventilation - rectangle		
Congestion – repeated obstacles	 Repeated obstacles	 Improved layout
Congestion vs. venting	 Equipment blocking vent area	 Improved layout
Ignition location	 Ignition at opposite end of vent location	 Ignition in vicinity of vent location

3.3.3 Loading direction

It should be recognised that the overpressure and drag loading, and the differential displacement loading, can have two lateral components and one vertical component. In most instances drag and overpressure will be dominant in one direction only; this will be discussed in more detail in future sections. In addition, the drag and overpressure loading will have a positive and negative phases as can be seen in Figure 30 and Figure 31.

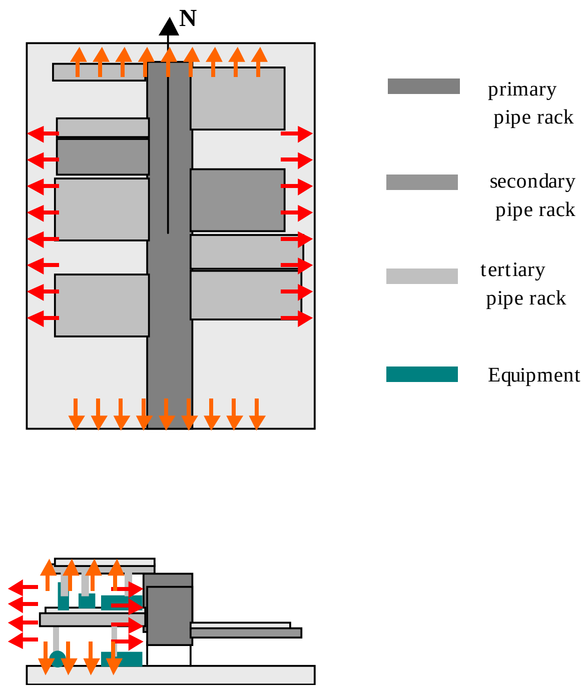


Figure 30 Drag and overpressure loading – positive phase

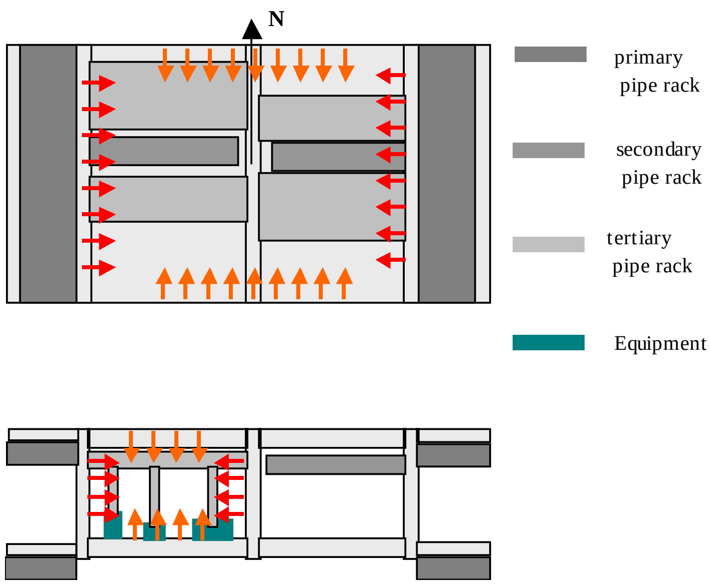


Figure 31 Drag and over pressure loading - rebound phase

3.3.4 Variation of loading with time

The drag and overpressure loading varies irregularly with time. In cases of design specifications and sensitivity studies, it is often useful if the loading can be simplified and linearised to a simple trapezoidal or triangular form. The other alternative is to model the exact time variation of the loading, which may be more sensitive to differences between what is modelled and what is constructed. This is possible with advanced structural analysis packages. Several studies have focused on linearization techniques including the gas explosion handbook, the Gas Explosion Model Evaluation Protocol (MEGE [38]) and the Interim Guidance Notes [2].

3.3.5 Overpressure and drag

The pressure distribution around a cylinder gives a time varying force in the stream-wise and the crosswise direction. The hydrodynamic force is given by the integrated normal and shear stresses over the surface of the obstacle. The following equation shows a phenomenological splitting of the hydrodynamic force:

$$F_h = \frac{1}{2} C_d A|U(t)|U(t) + (\rho V + m)\frac{\partial}{\partial t}(U) + \frac{\partial \rho}{\partial t} VU(t) + F_{DP(M)} + F_{HE}$$

The first term is given by quasi-static form drag depending on obstacle shape, surface roughness, fluid density and Reynolds Number. The second term is the inertia force proportional to the acceleration. This term consists of the buoyancy term of the obstacle in the accelerated flow field and an added mass term from the integrated normal stress 180 degrees out of phase with the bulk flow motion. The third term is a combustion contribution originating from the change of mass per unit volume in a generalised version of Newton's law. The fourth term is the differential pressure, which is a function of the Mach Number (U/c), where c is the velocity of sound. The last term is the hydro-elastic term.

3.3.6 Drag Loading

The force on a rigid, stationary object in a moving fluid is a result of the spatial and temporal variation in the fluid pressure and flow around that object. For example, a pressure wave passing the object will result in a time varying pressure gradient across it. In addition, the flow induced by the pressure wave, and otherwise, will be deflected by the object inducing further pressure gradients (due to normal stresses) and frictional forces (due to tangential stresses).

The drag force, a combination of the skin friction (tangential stresses) and the form drag (normal stresses), is commonly written as follows:

$$\mathbf{F_d} = \frac{1}{2} \rho A C_d |\mathbf{v}|\mathbf{v}$$

where ρ is the fluid density, A is the maximum cross sectional area of the object in a plane normal to $\mathbf{v}$, C_d is the drag coefficient and $\mathbf{v}$ is the large scale fluid velocity ignoring spatial fluctuations in the vicinity of the object.

Note also that in a turbulent flow the velocity term is actually a time-mean value, albeit over time-scales less than those of the large scale variation in the flow. This means that variations on turbulent time-scales are not included in this analysis. These include such effects as vortex shedding, in which vortices form alternately on one side and then another of the object. (The potential results of vortex shedding have been demonstrated in disasters such as the collapse of the First Tacoma Narrows bridge.)

The drag coefficient C_d depends on the shape of the obstacle and on the Reynolds number of the flow. The nature of *Cd* has been studied extensively for various standard shaped objects in steady flow. Its functional dependence on the Reynolds number is summarised in Figure 32 [39], for flow transverse to a cylinder. For low levels of turbulence the skin friction dominates. At higher levels of turbulence eddies form behind the object and the form drag dominates, as a result of which the drag coefficient levels out. This plateau corresponds to the commonly quoted values (e.g. see TNO Green book [40]) such as 1.2 for flow transverse to a cylinder and 0.82 for axial flow past a cylinder. The sharp drop around $Re=10^6$ is the so-called drag crisis, where a sudden onset of boundary layer turbulence, although increasing skin friction, moves the separation point further back on the object reducing the form drag.

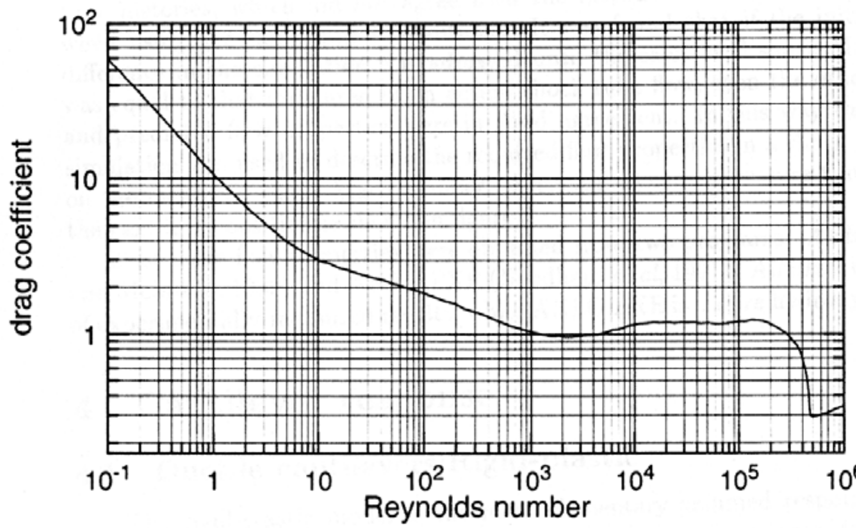


Figure 32 C_d as a function of Reynolds number (Schilting, 1960 [39])

The effects of transient flow (and the resultant modification to the drag force equation) are not well understood (and, in fact, are often misunderstood) even though they have been known for over one hundred years (e.g. Basset 1888 [41]). This area is perhaps best studied for spherical objects. Experimental work by Temkin and Mehta [42], for example, showed that for a sphere in oscillatory flow, transient effects could be modelled by the drag force equation by altering C_d. An accelerating flow reduced the drag and a decelerating flow increased it. It is thought that this is because acceleration of the flow is associated with a smaller recirculation region and vice versa. We will not consider this effect further, by assuming that the acceleration induced reduction and the deceleration induced enhancement compensate each other.

We approximate the pressure gradient force by the expression

$$\mathbf{F_p} = -Al\nabla p$$

where l is the length scale of the object in the direction of flow and p is the large scale pressure.

The drag coefficient is a function of the Reynolds number and the local Mach number of the flow. Both the Reynolds and the Mach numbers are functions of the time varying flow conditions and so the drag coefficient is also time varying. Figure 33 shows the dependence of the drag coefficient on the Mach (Hoerner, 1965) number [43]. If the Reynolds number is greater than 4 x 10^5, the flow is considered turbulent and the Mach curve shown in Figure 33 should be used. For lower Reynolds numbers, the Reynolds curve shown in Figure 32 should be used.

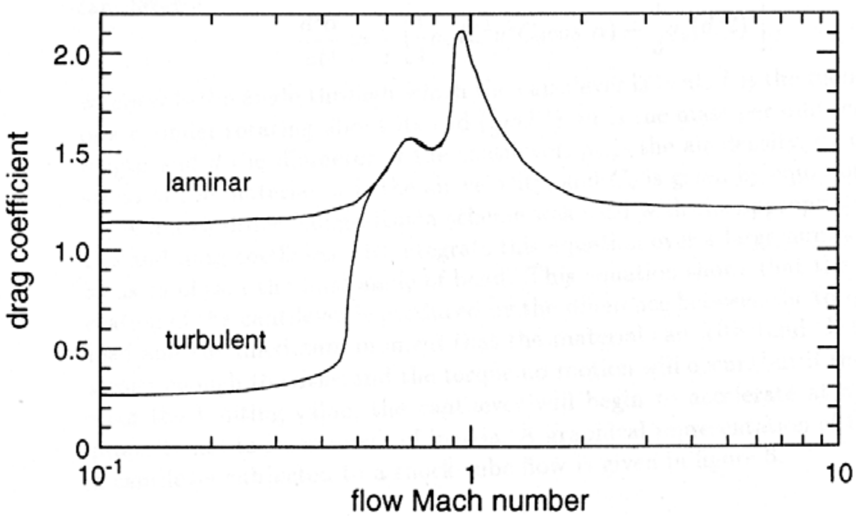


Figure 33 Variation of drag coefficient with Mach number

3.3.7 Differential movement of supports

In addition to overpressure and drag loading, piping systems may be subjected to large forces due to relative movement at supports. These are computed either by a coupled piping-topside structural response analysis, or by a decoupled piping analysis using the accelerations obtained from a topside structural analysis as input.

Decks on which equipment items are mounted are subjected to differential pressure loads, which induce vertical (and sometimes horizontal) acceleration of the equipment. Deck accelerations principally cause vertical movements and forces in the equipment but, when the equipment is tall and not located at the centre of the deck, the deck inclines locally as well as moving vertically. This will induce horizontal movements and accelerations at the centre of gravity of the equipment.

Deck pressure points should be nominated. This data will be used for calculating deck displacements and accelerations: (it is a good idea to produce spatial plots of differential pressure). Figure 34 [44] shows a segment of a typical deluge system, which may be subjected to differential acceleration if it is supported at various points along its length.

In many cases, differential deck acceleration can be a major cause of piping failure, more than loading due to either overpressure or drag.

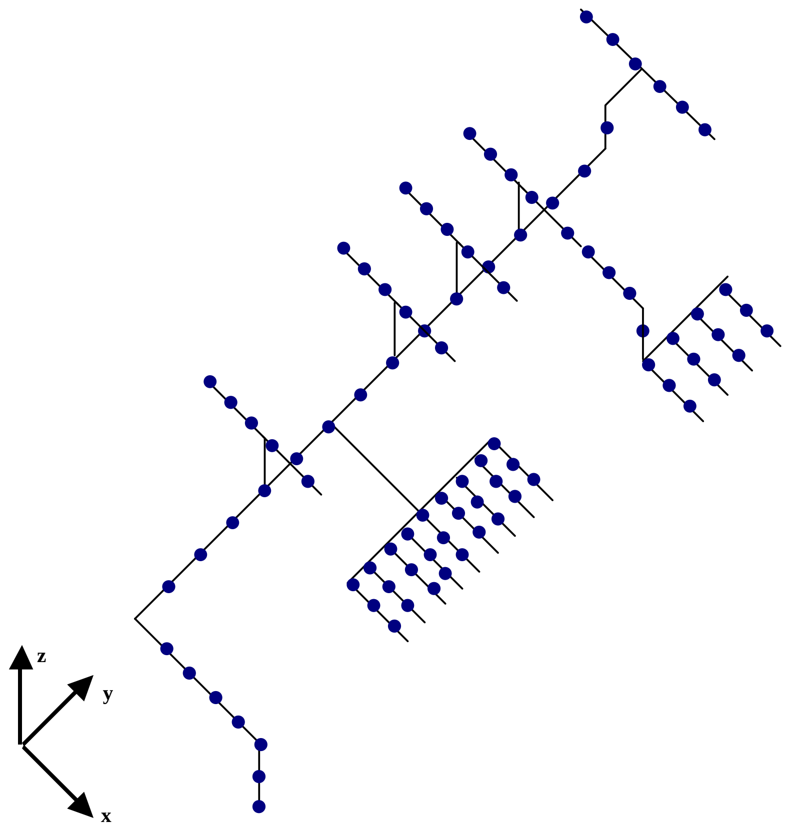


Figure 34 Segment of a typical deluge piping system

3.3.8 Case Studies and Experimental Results

This section reviews some of the results on explosion loading that have been reported in the literature.

Table 11 below shows results from the Explosion Model Evaluation Group [45, 46], showing the relative contributions of various loading components for a variety of pipe sizes and configurations.

Table 11 Explosion Model Evaluation Group: Three test cases

Test Case	Gas explosion velocity	Structure frequency relative to vortex shedding	Cylinder diameter	Major contributions
1	subsonic	High	50 mm	form drag inertial drag
2		Low	167mm (H)	ALL
3	Close to sonic		400 (V)	1.form drag 2. inertial drag 3. diff pressure

Case Study 1: Platform A [47]

Because the design criteria were established before detailed analysis results became available, there is likely to be a mismatch between the potential explosion phenomena and the design. Due to the fast-track nature of some projects, a pragmatic approach is adopted, whereby the design is created using a simplistic design basis and then verified by a detailed consideration of the blast loads expected from the detailed modelling.

The dynamic blast wind loads from the detailed modelling were found to be lower than the simplistic static design base and, therefore no further verification was pursued (accepting that slender structures could be considered over-resistant to blast).

Quasi-static overpressure loads were found to be higher than the simplistic basis in some cases. These loads apply primarily to walls and decks. The approach adopted in these cases was to perform a detailed blast load response analysis of the design, to define the blast loads at which deformation of the item first becomes plastic and then at which unlimited deformation (i.e. catastrophic disruption) of the item occurs.

Table 12 compares the original design basis with the results obtained by detailed modelling. As can be seen, in all cases items which are considered subject to dynamic loads have been designed to a higher standard than would be necessary. In some areas the criteria determined for static pressure loads exceed the design basis in some cases.

Table 12 Blast criteria

Area	Original design basis (kPa)	Criteria from Detailed modelling Walls (Static pressures) (kPa)	Piperacks (Wind Drag) (kPa)
Turret	75	130	Not used
P3	40	35	12
P1	50	35	12
P2	50	45	18.4
U1	50	45	18.4
U2A	22/11*	20	Negligible
U2B	0	20	Negligible
Accommodation	0	25	Not used/ negligible
* Considered shielded by U1 to a height of 6m. Higher criteria used above this height			

Case Study 2: FPSOs [48]

The table below summarises design overpressure values from various studies on various FPSOs.

Table 13 Overpressure due to explosions (barg)

Area / FPSO	Separation Area	Turret Area	Compressor Area	Between decks areas
A	0.48	0.55	0.64	0.37
B	0.35	0.35	0.64	0.37
C	0.7	0.7 (localised 1.2)	0.7	0.35
D	0.5	0.4	0.6	0.35

More work is required to understand the differences between the overpressures, in particular, whether they reflect improved trends in design, or simply different approaches adopted by various design houses.

3.3.9 Drag-overpressure relationship

Another approach is to try to generate a relationship between drag and overpressure. However, it is debatable whether such a relationship can be generalised to various platform types, and whether the effort is not better targeted towards generating drag exceedance curves. Figure 35, based on a recent FABIG Newsletter Article [44], below shows such a relationship.

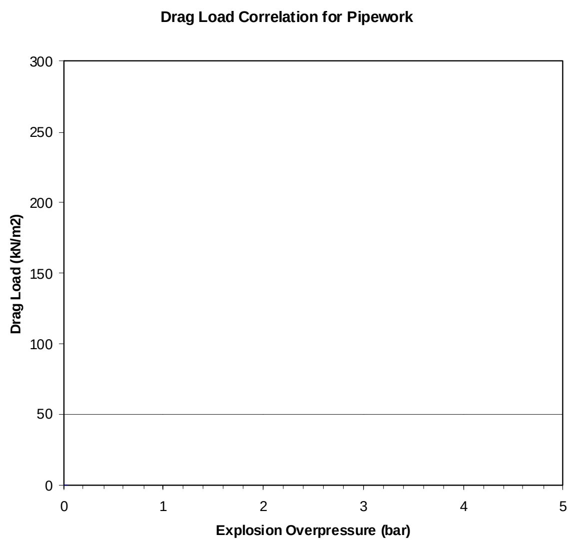


Figure 35 Drag overpressure relationship

Exceedance curves

Another approach for determining the loading due to an explosion event is to generate overpressure exceedance curves and drag loading exceedance curves, which may then be used with a particular return period. However, this approach is only used when a large amount of calculations are required. It is perhaps used when other more conservative methods generate very high explosion loading. The figure below [49] shows a typical overpressure exceedance curve. No drag exceedance curve is available in the open domain.

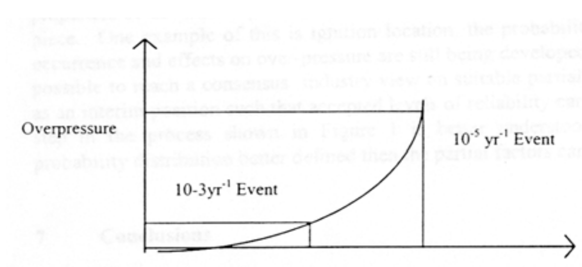


Figure 36 Overpressure Exceedance curve

3.4 TYPES OF PIPING AND MATERIAL PROPERTIES

The main types of steel used offshore are identified in this section. The relevant codes and standards are reviewed, and the high strain rate properties of commonly used offshore steels are presented. The elevated temperature properties are presented Chapter 4.

3.4.1 Standards used for piping and piping material

There are many different standards for piping and piping materials depending on the functionality of the piping. The main standards for steel piping for carrying combustible fluids are as follows:

- API Specification 5L Specification for Line Pipe [50]: The purpose of this standard is to provide standards for pipe suitable for conveying gas, oil and water in both the oil and natural gas industries. It covers seamless and welded steel line pipes. It also covers a variety of steel grades including X42 through to X80.
- BS EN 10208 Flat products made of steels for pressure purposes – Part 2:1993 Non-alloy and Alloy steels with specified elevated temperature properties [51, 52 and 53]: The purpose of this code is to specify requirements for flat products for pressure purposes made of weldable non-alloy and alloy steels with elevated temperature properties. The code covers a variety of steel grades including P235GH to P355GH.
- ASTM A106: Standard Specification for Seamless Carbon Steel Pipe for High-Temperature Service [54]: This specification covers seamless carbon steel pipe for high-temperature service for Steel A106 Grade A, A106 Grade B and A106 Grade C/
- ASTM A333: Standard specification for Seamless and welded steel pipe for low temperature service [55]: This specification covers seamless and welded carbon and alloy steel pipe intended for use at low temperatures. It covers a variety of Grades from A 333 Grade a through to A333 Grade 11.
- ASME B31.3 Process Piping – Chapter III Materials [33]:
- BPVC Section III – Rules for the Construction of Nuclear Power Plant Components – Div 1 – Subsection NC-Class 2 Components and Subsection NC – Class 3 Components [56]: This code provides a useful example of how a risk based methodology may be used for the analysis of piping against fire and blast.
- Structural Analysis and Design of Nuclear Plant facilities, 1980, Committee on Nuclear Structures and Materials of the Structural Division, ASCE [57]***:*** This code provides a useful example of how a risk based methodology may be used for the analysis of piping against fire and blast.
- FABIG Technical Note 6 [7]: Elevated Temperature and High Strain Rate Material Property Data of Offshore Steels: The purpose of this document is to provide guidance on elevated temperature and high strain rate property data that is currently available for high strength steels used specifically for offshore structures. The document covers a variety of steel grades including Grades 355EMZ and 450EMZ.

For piping that does not carry combustible fluids, the following standards may apply:

- BS EN 10216-1:2002 and BS EN 10217-1:2002 Welded and seamless steel tubes for pressure purposes [58 and 59]
- BS EN 10216-2:2002 and BS EN 10217-2:2002 Welded and seamless steel tubes for pressure purposes with specified elevated temperature properties [60 and 61]

- BS EN 10216-4:2002 and BS EN 10217-4:2002 Welded and seamless steel tubes for pressure purposes with specified low temperature properties [62 and 63]
- BS 3604 Steel pipes and tubes for pressure purposes. Ferritic alloy steel with specified elevated temperature properties [64]
- BS 3605 Austenitic stainless steel pipes and tubes for pressure purposes[65]

3.4.2 Typical Materials used

Based on meetings with various offshore contractors, the following types of material used offshore are identified below:

- 316L,
- X52/X65 (API 5L),
- Carbon Steel A333 Grade 3 and Grade 6, ASTM
- Duplex Stainless Steel,
- GRE (24 and 18 inches), and
- Copper nickel for water deluge.

The table below summarises the typical material for piping used offshore and relates it to the relevant code discussed in Section 3.4.1 above:

Table 14 Typical material used for piping

Code / Grade	API 5L	BS EN 10208	ASME B31.3	BPVC Section 3	FABIG Technical Note 6
316L	✓	✗	✗	✗	✓
X52/X65	✗	✗	✓	✗	✗
A333 Grades 3 and 6	✓	✗	✗	✗	✗
Duplex Steel	✗	✗	✗	✗	✓
GRE	✗	✗	✗	✗	✗
Copper nickle	✗	✗	✗	✗	✗

3.4.3 Material properties to account for strain hardening effects

For general design in stainless steel, the design strength σ_y is taken as the minimum specified 0.2% proof strength $R_{p0.2.}$ However, when blast loading is being considered, the design strength may be enhanced to σ_{dyn}, to take advantage of the improvement in strength due to the high strain rates, where:

$$\sigma_{dyn} = \sigma_y \left(K_{SR}\right)_{0.2}$$

The enhancement of stresses as a result of high strain rates can also be represented by the Cowper - Symonds empirical relationship. The Cowper-Symonds constants D and q, for 316L, SAF2304 and 2205 stainless steels, which have been obtained from a least mean squares fit, are given in Table 3.7.

Table 15 Cowper – Symonds constants for stainless steels

Material	Proof strength	D s^{-1}	q	σ_0 MPa
316L	0.1%	471	5.76	263
	0.2%	240	4.74	277
SAF 2304	0.1%	22.0 635 (alt)	2.51 4.04 (alt)	516
	0.2%	3489	5.77	527
2205 (318)	0.1%	769	5.13	544
	0.2%	5958	6.36	575

Cowper Symonds relationship: $\dfrac{\sigma_d}{\sigma_s} = 1 + \left(\dfrac{\dot{\varepsilon}}{D}\right)^{\frac{1}{q}}$

Where

σ_d is the dynamic stress at a particular strain rate, $\dot{\varepsilon}$ and

σ_s is the static stress

Table 16 and Table 17 and give values of the strain rate enhancement factor K_{SR} for the 0.1%, 0.2% and 1% proof strengths for a range of pre-yield strain rates $\dot{\varepsilon}_y$. Values of K_{SR} for the ultimate tensile strength $((K_{SR})_u)$ for a range of post-yield strain rates $\dot{\varepsilon}_u$ are also given alongside the rupture strain ε_f.

Using the strain rate enhancement factors, given in Tables 3.8 and 3.9, it is possible to construct a simplified linearised stress-strain curve for a particular strain rate. A family of curves can be generated for a range of strain rates thereby producing fully enhanced stress-strain curves. These curves can then be used for assessments of the plastic deformation using non-linear finite element analysis. Figure 3.17 shows one such stress-strain curve for a single strain rate.

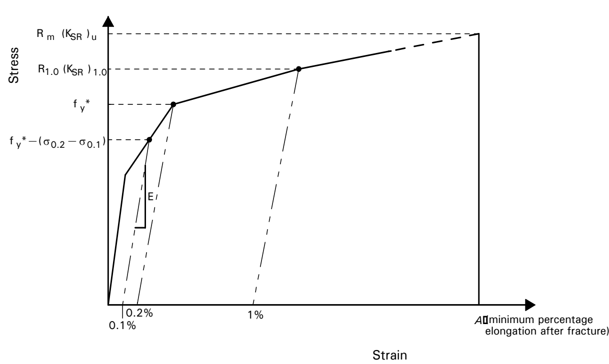


Figure 37 Linearised stress strain curve with strain rate effects

Table 16 Strain rate enhancement for 0.1%, 0.2% and 1.0% proof

Grade	$\dot{\varepsilon}_y$ (s^{-1})	$\sigma_{0.1}$ (N/mm^2)	$(K_{SR})_{0.1}$	$\sigma_{0.2}$ (N/mm^2)	$(K_{SR})_{0.2}$	$\sigma_{1.0}$ (N/mm^2)	$(K_{SR})_{1.0}$
1.4404 (316L)	1.38e-4	269	0.93	276	0.92	316	0.94
	0.0017	287	0.99	296	0.99	332	0.99
	0.0025	291	1.00	300	1.00	335	1.00
	0.0086	304	1.04	313	1.04	346	1.03
	0.0178	311	1.07	321	1.07	352	1.05
	0.0880	327	1.12	338	1.13	366	1.09
	7.4200	372	1.28	385	1.28	404	1.21
1.4362 (2304)	1.38-04	525	0.97	548	0.96	615	0.97
	9.9e-4	536	0.99	562	0.98	626	0.99
	0.0025	543	1.00	572	1.00	634	1.00
	0.0055	549	1.01	581	1.02	641	1.01
	0.0111	555	1.02	588	1.03	647	1.02
	0.1000	572	1.05	613	1.07	666	1.05
	5.3900	604	1.11	656	1.15	700	1.10
1.4462 (2205)	1.38e-04	565	0.95	596	0.95	680	0.96
	0.0024	591	1.00	627	1.00	705	1.00
	0.0025	592	1.00	627	1.00	705	1.00
	0.0055	601	1.02	638	1.02	715	1.01
	0.0112	610	1.03	648	1.03	723	1.03
	0.1230	639	1.08	682	1.09	751	1.07
	6.4800	688	1.16	737	1.18	797	1.13

Table 17 Strain rate enhancement for 0.1%, 0.2% and 1.0 % proof strengths

Grade	$\dot{\varepsilon}_y$ (s^{-1})	σ_u (N/mm^2)	$(K_{SR})_u$	ε_f GL = 60-mm(%)
1.4404 (316L)	1.38e-04	597	0.97	58.7
	1.69e-03	615	1.00	-
	2.50e-03	619	1.01	49.3
	8.63e-03	628	1.02	50.3
	1.78e-02	632	1.03	50.0
	8.80e-02	644	1.05	51.0
	7.42e+00	658	1.07	52.7
1.4362 (2304)	1.38-04	739	0.98	36.0
	9.90e-04	754	1.00	-
	2.5e-03	758	1.01	28.0
	5.50e-03	766	1.02	26.0
	1.11e-02	769	1.02	29.7
	1.00e-01	779	1.03	29.0
	5.39e+00	790	1.05	30.7
1.4462 (2205)	1.38e-04	813	0.97	34.3
	2.40e-03	841	1.00	-
	2.50e-03	847	1.01	29.0
	5.53e-03	862	1.03	29.3
	1.12e-02	867	1.03	30.0
	1.23e-01	887	1.05	30.0
	6.48e+00	905	1.08	28.3

3.4.4 Summary

Material properties at high strain rates are required for determining the response of piping to explosions. The Table below provides a summary of available high strain rate material properties data for the commonly used offshore steels. It can be seen that there is sufficient data for stainless steels 316L and duplex as a result of work carried out by the SCI and reported in FABIG Technical Note 6 [7]. Further research and experimental tests may be required to generate the missing data, marked with a ✗, in the Table below.

Table 18 Availability of high strain rate material property data

Property \ Steel	316L	X52/X65 (API 5L)	A333 Grades 3 & 6	Duplex	GRE	Copper-Nickel
Elasticity Modulus	✓	✗	✗	✓	✗	✗
Poisson's Ratio[i]	✗	✗	✗	✗	✗	✗
UYS©	✓	✗	✗	✓	✗	✗
LYS©	✓	✗	✗	✓	✗	✗
UTS©	✓	✗	✗	✓	✗	✗
Rupture Strain	✓	✗	✗	✓	✗	✗
Stress-Strain curves	✓	✗	✗	✓	✗	✗
i. It is assumed that Poisson ratio does not vary with strain rate						

3.5 RESPONSE OF PIPING TO BLAST LOADING

The response of piping to blast loading may be determined using: either single degree of freedom (SDOF) methods; or using multi degree of freedom methods, such as the finite element method. The main problem with SDOF method is that it is only feasible to apply to structures which can be characterised by a single stiffness and the loading by a single time varying curve. With overpressure loading, drag loading and forces due to relative movements of the supports, there are always at least two separate load quantities acting in different directions and with different time variation. In this case, errors are likely to arise when using SDOF methods.

In cases where the drag loading is confined to one direction, and where the overpressure loading is negligible, the problem in applying SDOF method is reduced to how to combine a drag load in one direction with deck acceleration effects. This becomes more of an issue when non-linear effects have to be accounted for, to take advantage of the ductility of the system.

In all cases the forces caused within the piping item and its supports are dependent upon:

- the mass and stiffness of the piping system,
- the stiffness of the support structure, and
- the ductile deformation capacity of the piping system and its supports.

3.5.1 Selection of method of analysis

Figure 38 [6] shows the steps that should be taken to select an appropriate method of analysis. The geometric and material properties of the piping system, and its supporting structure, are obtained and the relative frequency of the two is compared. The design loads acting on the piping are selected based on the criticality rating of the piping.

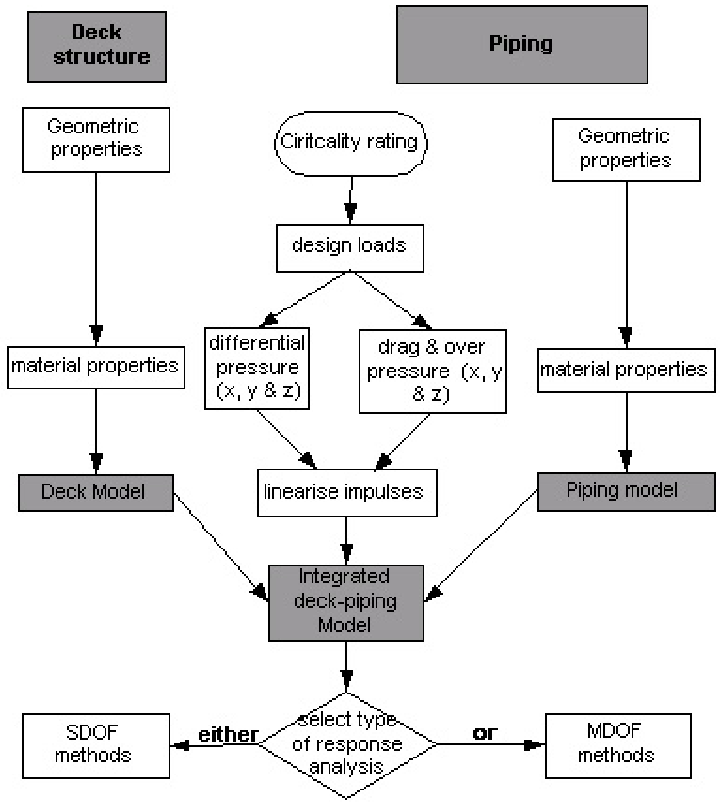


Figure 38 Selection of method of analysis

3.5.2 Procedure for analysis using linear SDOF methods

The objective of the SDOF method is to translate a dynamic pressure or load into an equivalent static load for the piping and equipment design. The equivalent static loads are the peak dynamic loads found in time. It is important to evaluate the maximum positive and negative deflections and forces. The time domain simulation requires the preparation of two separate idealised models of the piping system item and support structure [6]:

1. Apply the peak explosion load to the model multiplied by a suitable dynamic load factor (DLF)

2. The negative or rebound response will be a further load case where the peak explosion load is multiplied by the rebound dynamic load factor (RDLF), which has the opposite sign of the DLF

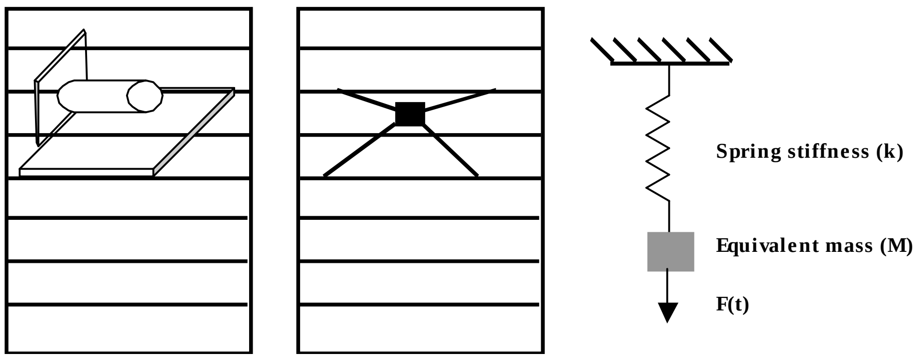
3. Treat the loading in the x-, y- and z-directions as separate load cases

4. Finding DLF and RDLF requires the modelling of piping and its surrounding support structure

5. The SDOF model is an idealisation of the piping and its support structure, where the spring has a stiffness K such that the mass M_e has the same deflection as the mass centroid piping item when subject to the same load. Mass M_e is the mass of the equipment multiplied by a transformation factor whose value is such that the period of

vibration of Model 2 is the same as that for Model 1 for the appropriate vibration mode shape (See Figure 39)

6. The x- and y- direction forces are drag force components , the z-force acting is the differential pressure across the deck. The mode of vibration will be different for each direction hence the natural period of the SDOF Model 2, the spring stiffness and mass M_e will be different for each of the directions. The force time histories will have different shapes and maxima. It is necessary to consider x-, y- and z-directions separately and obtain DLF and RDLF for each direction and then sum the worse values of DLF and RDLF for application in the SDOF model.



(a) Problem definition **(b) Model 1: Structural response analysis** **(c) Model 2: SDOF Analysis**

Figure 39 Equipment models for developing single degree of freedom models

3.5.3 Procedure for accounting for deck accelerations in the SDOF analysis

The deck is deflected and accelerated principally by the vertical component of the loading. The deck accelerations will cause inertia loads in the piping and piping supports which must be taken into account. In addition piping with multi point attachments will be subjected to differential displacements at each of its supports. Deck accelerations may be determined using SDOF analysis using the following procedure:

1. Identify reference points where the deflection / acceleration need to be determined.

2. Apply a unit differential pressure to Model 1 in Figure 39. Note that Model 1 should include all parts of the structure where deflection reference points identified in 1 are needed.

3. Determine the deflection / acceleration at the reference points corresponding to a unit differential pressure.

4. Determine natural period of the deck for vertical movement

5. Determine equivalent mass and stiffness of SDOF model (Model 2 in Figure 39).

   a. The mass is considered the total mass of the deck and the equipment multiplied by the load mass factor K_{LM}, which may be determined from tables in the Interim Guidance Notes [2].

b. The stiffness is then determined such that the mass determined in step (a) above will have the same deflection under an applied load equal to the unit load multiplied by the deck area.

6. The load is a force time history equal to the linearised deck pressure multiplied by the deck area.

7. Apply the load from step (6) to the SDOF system defined in step (5) to determine the displacements and accelerations at the reference support points.

3.5.4 Procedure for accounting for piping ductility in SDOF analysis

Plastic deformation of the piping or the piping supports will absorb the dynamic energy, and will lead to a significant reduction in the dynamic load factors (DLF and RDLF). Ductility can be accounted for by modifying the stiffness to be used in the SDOF model (Model 2 in Figure 39). The stiffness can be modified in one of the following ways:

1. Use an equivalent stiffness of R_p / d_{el}

2. Use the three part curve shown in Figure 40

Allowable deflection limit is often expressed in terms of a ductility ratio defined as d_{el}/d_p. The Interim Guidance Notes [2] provide charts with dynamic load factors (DLFs) for various ductility ratios. Care must be taken to ensure that any weak members or connections will not fail before the deflection corresponding to the ductility ratio under consideration is reached.

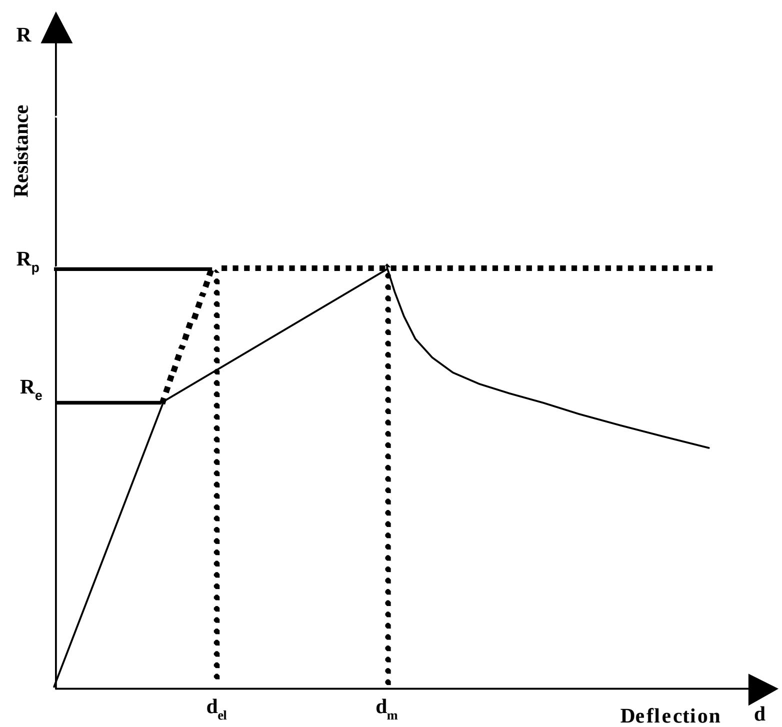


Figure 40 Idealisation of non-linear load deflection characteristics

3.5.5 Multiple Degree of Freedom Analysis

Where a structure cannot be idealised as SDOF, the only general method for determining its dynamic response to explosion loading is by finite elements. In such cases the piping system together with the support structure should be modelled. Either decoupled or coupled analysis should be carried out. If the piping system is considered to have a significant effect on the topside structure then a coupled analysis should be carried out (e.g. this is usually done in the case of risers). In case the piping effect on the system can be simply represented by an additional mass then a decoupled analysis may be carried out. If the period of vibration of the piping system and the topside structure are of sufficient proximity such that resonance may occur, then a coupled analysis should be carried out.

3.6 ACCEPTANCE CRITERIA

Table 19 summarises the damage that has been reported to various equipment and piping systems. This is an extract of a more complete table presented in the Explosion Handbook [4]. It can be seen that various degrees of damage is often experienced by a variety of piping systems and piping attached to equipment. It is not reasonable to design against all kinds of damage, and so acceptance criteria are developed to set tolerable limits to damage.

The main acceptance criteria that are usually considered for piping systems are:

- Strength limit
- Strain (rupture limit)
- Deformation limit
- Ductility limit

3.6.1 Strength Limit

Failure is defined as occurring when the design load or load effects exceed the design strength . The criterion may be applied in the elastic as well as plastic regimes. Modified factors for loading and strength may be adopted to account for the fact the blast is an extreme event.

Table 19 Reported damage to piping and equipment

Equipment \ Overpressure (barg)	0.03	0.07	0.10	0.14	0.17	0.20	0.24	0.27	0.30	0.34	0.37	0.41	0.44	0.48	0.51	0.54	0.60	0.61	0.65	0.68	0.82	0.95	1.09	1.2	1.36	1.36
Cooling tower	2		4				3																			
Tank: cone roof		3				9							19													
Fired heater				5	7					18																
Chemical reactor				1				?					14					18								
Filter				6					4										20		18					
Regenerator										14					15											
Tank: floating roof						9							19												3	
Pipe supports							14					17 13														
Gas meters									15																	
Electrical motors										6								10								20
Blower										15										18						
Fractionation column											16				18											
Horizontal pressure vessel												14 7						18								
Extraction column													7							20	18					
Stream turbine															10						11	17				20
Heat exchanger															10			18								
Tank sphere																8							7	18		
Vertical pressure vessel																					7	18				
Pump																					10		20			

Notes: 1. Windows and gauges break, 2. Louvers fall at 0.3 to 0.5 psi; 3. Roof collapses; 4. Damage to inner parts; 5. Brick cracks; 6. Projectile damage; 7. Unit moves and pipe breaks; 8. Bracing fails; 9. Unit uplifts; 10. Power lines severed; 11. Controls damage; 12. Block wall fails; 13. Frame collapses; 14. Frame deforms; 15. Case damaged; 16. Frame cracks; 17. Piping breaks; 18. Unit overturn and/or collapse; 19. Unit uplifts; 20. Sliding/rocking motion

3.6.2 Strain Limit

Strain rupture limits under high strain rates are available for stainless steels. For other steel types approximate values have to be used. Table 3.6 of the Interim Guidance Notes provides strain limits for different classes of steel sections.

3.6.3 Deformation Limit

This criterion reflects the fact that under large deflections the pipe may rupture from its support or the point of connection to other equipment.

3.6.4 Ductility limit

A minimum ductility limit may be set to a ductile response under blast loading. Table 3.7 of the Interim Guidance Notes provides ductility ratios based on strain limits.

Figure 41 [66] shows typical escalation loads to equipment and to structure, where it can be seen that escalation to equipment occurs at much lower loads than escalation to structures.

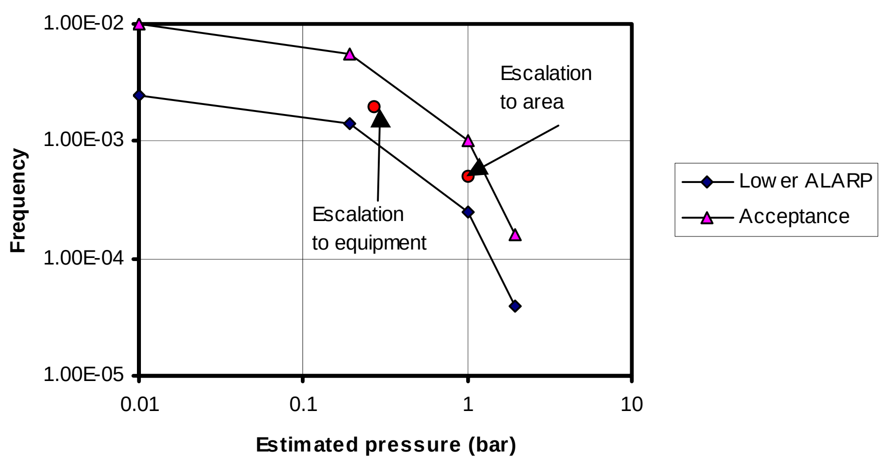


Figure 41 Comparison of typical 'escalation loads' to equipment and structure

3.7 GUIDELINES FOR DUCTILE CONSTRUCTION

Referring to the discussion in Section 3.5.2, DLF and RDLF, which are used to define the loading in the positive and the rebound phases, can be reduced by a factor of three or more if ductile construction is used. This is particularly true for items with long periods of vibration. The following points should be considered when adopting a strategy for ductile construction:

3.7.1 Piping

Material behaviour

- Ductile capacity is very dependent on the shape of the material stress strain curve in the strain hardening region.
- Piping response is more likely to be ductile if the material is ductile with yield to ultimate less than 0.7 or 0.8.

- Composites like GRP and GRE have a yield to ultimate tensile strength of 1.0 and therefore load reduction due to ductility cannot be taken into account.
- Ductility of material does not always lead to a ductile structural behaviour because the failure mode can be brittle, e.g. buckling.

Structural behaviour

- Response and resistance is dependent on whether piping component can deform in a ductile way
- Test data for pipes and fittings subject to ductile bending while under pressure does not appear to exist
- Piping without fittings will often have an elasto-plastic response; however, the assumed ductility of the pipe should be checked against the fracture strength of the material.
- In practice, many pipe spans do not incorporate weak links, and in those which do it is sometimes possible to arrange support locations so that weak links are away from the points in the pipe where bending moments are a maximum
- If plastic hinges form in components which are inherently ductile and the bending moments in components that are weaker or are nor ductile are within the static capacity of the components then a ductile bending behaviour can be assured for the line as a whole.

3.7.2 Analysis

- Implicit type nonlinear finite element analysis cannot be used reliably because they cannot handle increasing deflection with decreasing strength
- Do analysis to get a solution in the form of a distribution of bending moments in the pipeline that will result when the yielding capacity of the pipe is reached at points where plastic hinges will form

3.8 SPECIFIC FPSO ISSUES

On FPSOs it is normal to locate the process equipment on a raised deck or pallets above the main hull deck. This forms a barrier between the tanker piping which is a lower explosion hazard, and the process piping; it also reduces the extent of green water on the deck in storms and leads to more room for process equipment and a more manageable construction methodology.

On large FPSOs the process zone can be very extensive and congested and can outgrow the single deck principal. Pipe support design then becomes quite difficult because, unlike a fixed platform, there are no readily available strong decks to which the higher level pipe racks can be fixed. The problem is not how to design the supports of the equipment and pipes, but rather it is one of deciding what sort of above deck space frame should be constructed to tie the pipe supports back to.

Another aspect of the FPSO is that the deck is large and usually open so that an explosion will have effects over a wide area as can be seen from Figure 42 [67]. On fixed platforms it is possible to locate safety routes and control lines at different levels, and to provide isolation between levels with solid decks (as can be seen from Figure 43[68]. With FPSO design this is only feasible where the process deck is solid: a problem occurs if the turret is between the process area and the TR.

3.8.1 Layout issues

Main pipe racks: this runs parallel to the dominant blast wind direction. In practice, transverse wind effects are least at the centre line of the FPSO where the pipe rack is usually located as can be seen from Figure 44 [6]. Pipe racks have a significant number of transverse beams so longitudinal forces will be significant. Where the piperack is diverted to run transverse to the axis of the FPSO, severe sideways wind loads can be expected. Main piperacks on fixed platforms are usually located at the edges of the platform as can be seen from Figure 45 [6].

Secondary and tertiary pipe racks are subject to the most severe loading in the N-S direction (see Figure 44). They have to be supported from an overhead grillage of beams, which in turn are supported by portal frames. When the quantity of tertiary racking is included, the overall N-S force becomes large and it is not easy to see how the force can be resisted unless a brace frame concept is adopted for the whole superstructure. The forces in the bracing will be almost entirely explosion wind driven: hence the overall stability of the pipe racking will depend on the stability of the frame.

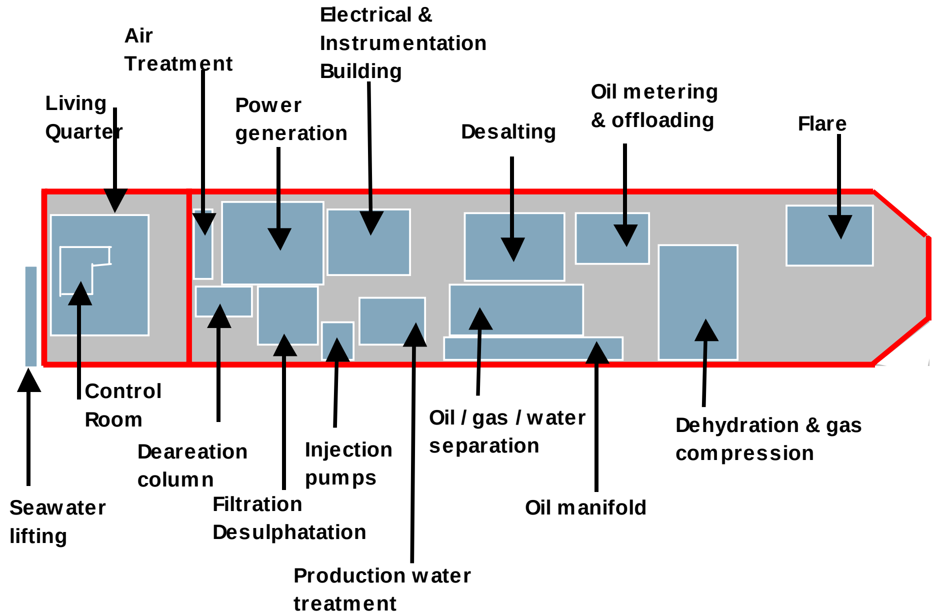


Figure 42 Detail FPSO layout

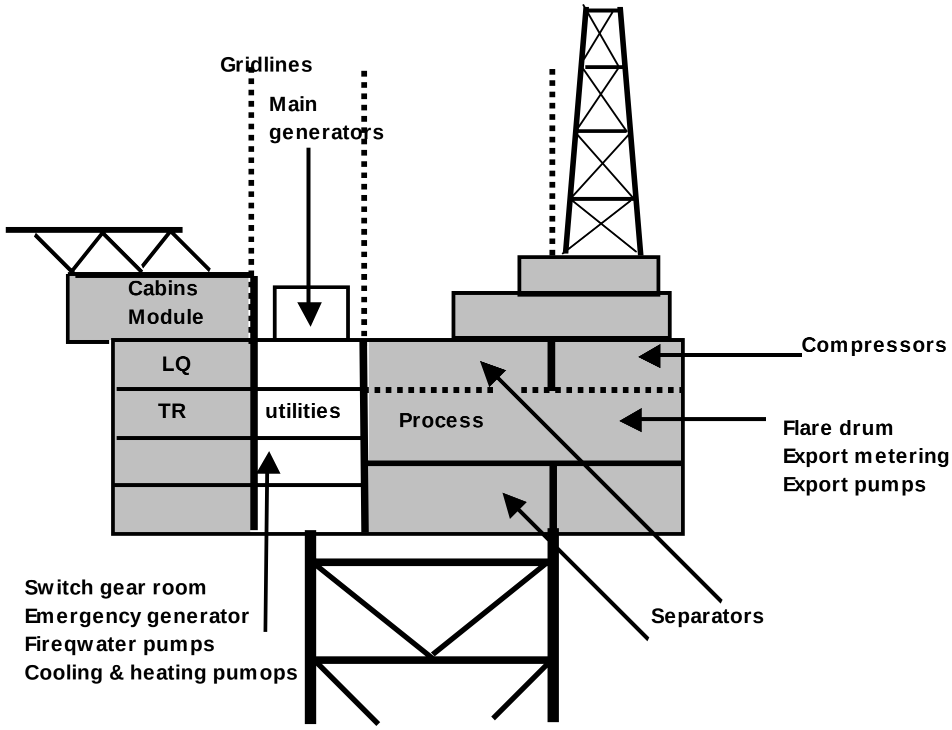


Figure 43 Fixed structure layout

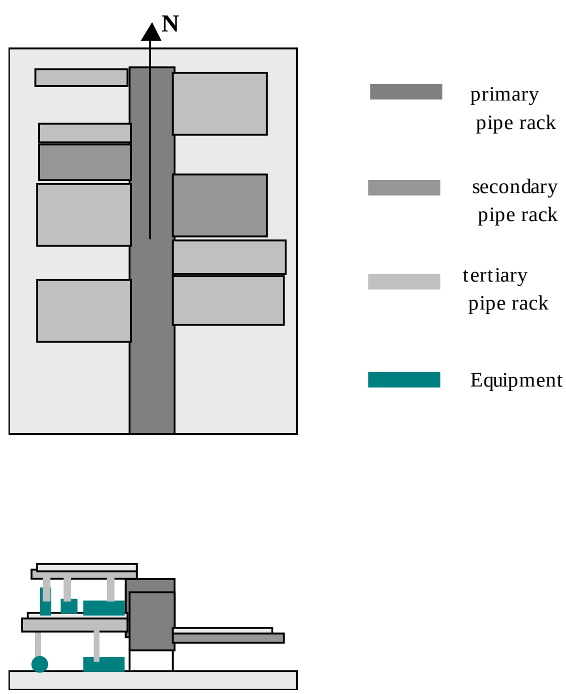


Figure 44 Typical Piping layout on an FPSO

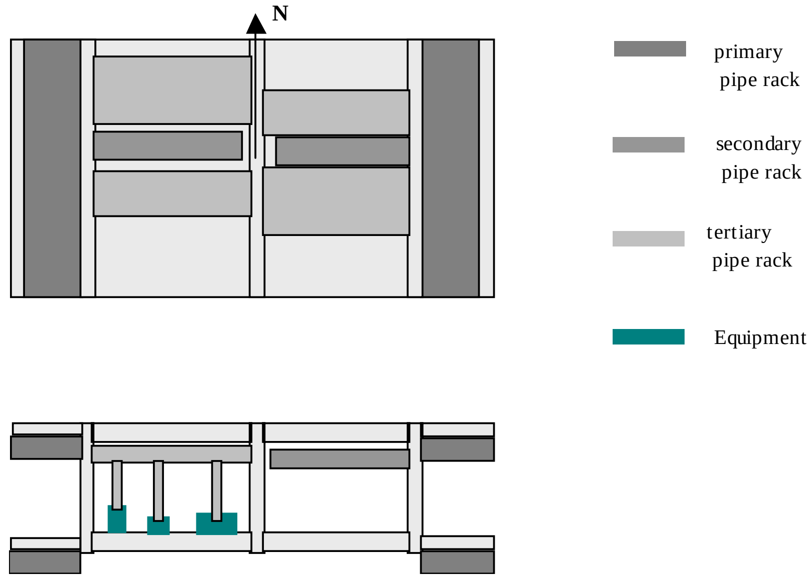


Figure 45 Typical piping layout on a fixed structure

4 DESIGN OF PIPING SYSTEMS AGAINST FIRES

4.1 INTRODUCTION

This Chapter considers the techniques that may be used to determine fire loads and their effects on piping systems. Section 4.2 presents a discussion on the interaction of fires and explosions. Section 4.3 prevents a review of the types of fires and the corresponding heat fluxes. Derivation of temperature loads from heat fluxes is discussed in section 4.4. Section 4.5 discussed passive and active fire protection systems. Section 4.6 provides material data for structural steels at elevated temperatures. Section 4.7 provides a review on design of piping systems against fire loading. Finally section 4.8 summarises outstanding issues where future effort should be directed.

4.2 INTERACTION OF FIRES AND EXPLOSIONS

Figure 46 presents the event tree showing various typical consequences after release. It can be seen that a release of a hazardous gas or liquid can lead either to 1.no ignition, 2. immediate ignition and subsequent fire (no explosion) or 3. formation of a combustible cloud which then may lead to a delayed ignition and gas explosion, which in turn may have various consequences varying from no damage to damage to personnel and property, and varying from no fire to fire and BLEVE (Boiling Liquid Expanding Vapour Explosion).

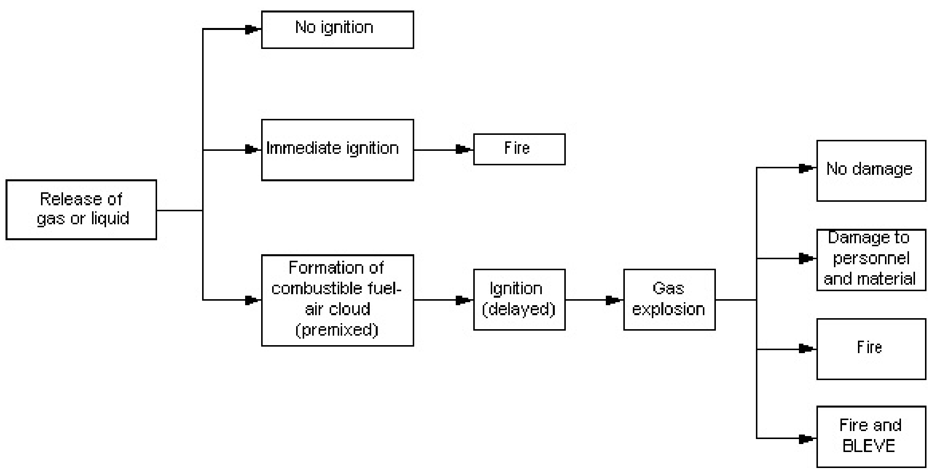


Figure 46 Event Tree showing typical consequences after release

Putting the above consequences in the now familiar ALARP triangle, see Figure 47 below [69], we can see that fires have a larger frequency of occurring before an explosion and that the delay of fires and the subsequent ignition and occurrence of explosions has a higher consequence. However it also possible to get very severe consequences from severe fires which occur at a much lower frequency. The severity of fires will depend on the fire type, which is discussed in the next section.

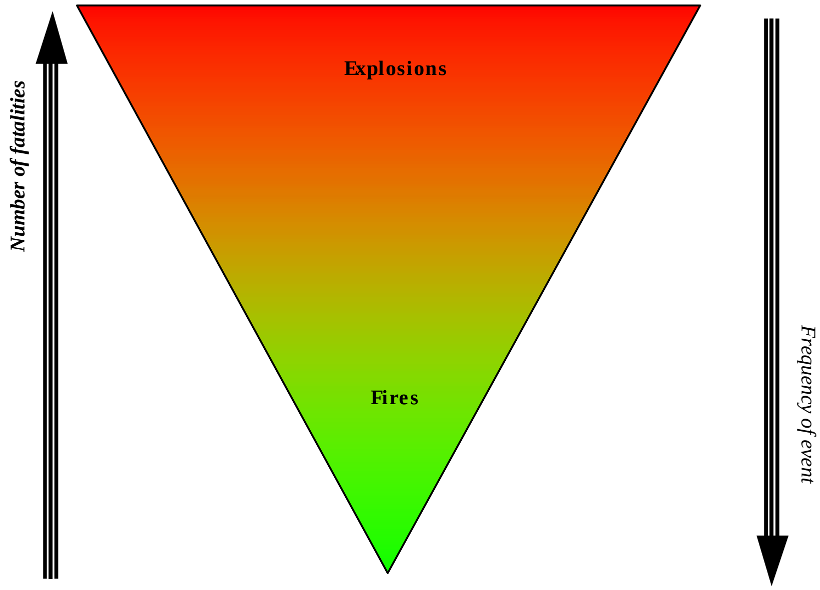


Figure 47 Risk due to initial fire or explosion

4.3 TYPES OF FIRES AND CORRESPONDING HEAT FLUXES

The heat flux available from a fire may be determined using various models which may be subdivided into three broad categories:

- Empirical models
- Field models (numerical or computational fluid dynamic models) and
- Integral (phenomenological models)

These have been discussed in the Phase 1 [1] Fire Loading reports and the Interim Guidance Notes[2]. In these studies, it was generally accepted that the semi-empirical models provide the most accurate and reliable prediction of the physical hazards associated with fires, provided that they are applied within the validated limits of the model. While this conclusion remains valid today, CFD models are developing rapidly and are expected to improve in accuracy over the coming years [8].

Several documents provide values for total incident heat flux for various fire types: The Interim Guidance Notes [2], Fire and Blast Engineering Project Phase II [3], The Norsok Guidelines [70], Scandpower Guidance [9] and the Institute of Petroleum guidance [71]. As more tests are carried out these values tend to change to reflect the latest data. The table below summarises the heat fluxes due to various fire types, as reflected in the latest studies. For each fire type, where available, both maximum and average heat flux values are provided. Maximum heat flux refers to the scenario where the flame engulfs the whole target, while average heat flux is averaged inside and outside the flame.

Table 20 Heat flux values for various fire types (kW/m^2)

Type of fire	Initial heat flux density	
	Maximum point loads	Average load
Pool fire (crude) open or enclosed area fuel controlled	150	100
Pool fire enclosed area ventilation controlled	200	130
Very large pool fire on sea due to Subsea gas release	250 – 300	100
Jet fire (crude) open or enclosed area fuel controlled	400	
Jet fire enclosed area ventilation controlled	400	

The following observation may be drawn on the recent findings on heat flux determination [8]:

- On the whole, the information given in the Interim Guidance Notes [2] remains valid for all the fire scenarios which concern jet fires and pool fires in the open, although it is worth noting that new information is now available in the case of two-phase jet fires. The information given for jet fires and pool fires in a module is somewhat outdated in light of recent advances in experimental and theoretical work.
- Unconfined Two-Phase Jet Fires: The incident total heat fluxes (radiative and convective) measured on the pipe target were significantly higher for the mixed fuel tests than for the crude oil only tests, by a factor two in many cases. Typical values were in the range 50 kW m^{-2} to 400 kW m^{-2}.

Figure 48 shows the fire hazard assessment framework, based on a similar flowchart produced by Cook and Phelp [72], where it can be seen that the fire load determination plays an important role in the consequence assessment of an offshore platform against fires and explosions. It comes after the identification of potentially flammable releases and their frequency, and it is a prerequisite to determining the response of structures to an ensuing fire. The boxes with dark shading are those tasks where the piping is expected to play an important role in the hazard management process.

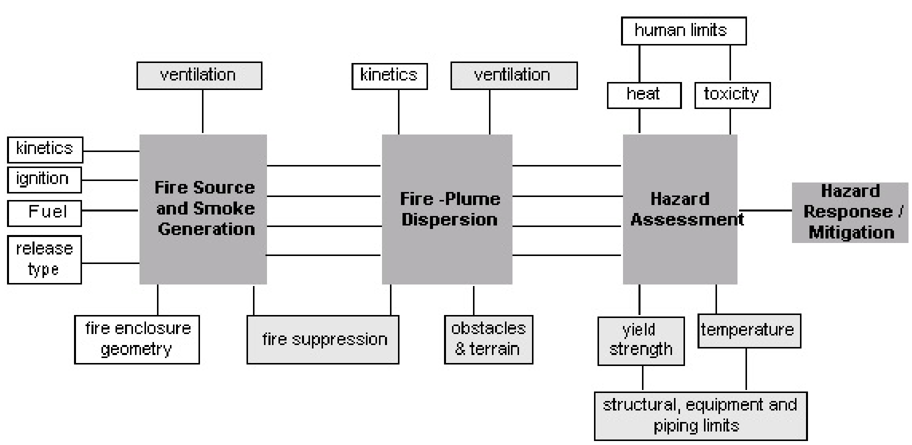


Figure 48 Fire Hazard Management Diagram

4.4 DERIVATION OF TEMPERATURE FROM HEAT FLUXES

The fire loading acting on the structure is expressed in terms of a temperature loading, while heat radiating from fires is usually expressed in terms of heat fluxes. As can be seen from the Table 4.1, one of the main factors affecting the thermal loading of piping systems is its location relative to the fire (engulfed or not engulfed). It should be recognised that in addition to receiving radiation from the hot flame, a non-engulfed surface may also receive re-radiation from other surfaces. In certain instances, e.g. compartment fires, the re-radiation component may considerably increase the total received flux.

To calculate structural response, it is important to calculate the average piping core temperature against time. However most of the work in the literature refers to the computation of steel core temperatures. This is summarised below, and a more detailed discussion may be found in the Interim Guidance Notes.

The computation of steel core temperatures may be carried out using one of the following methods:

- Finite difference and finite element methods
- Theoretical methods
- Heat dose method

Finite difference method: this is inherently suited for solving the heat flow through sections subjected to a prescribed rate of surface temperature rise (T).

Theoretical methods: An alternative to finite difference modelling approach is to adopt the equations for one-dimensional passage of heat through thin and thick fire protection material.

Heat dose method: this method can be used to compute the effect of a fire on a particular part of a module. It can only be used when release size and fuel type are known.

More detailed discussion is available in the Interim Guidance Notes [2] and references therein.

4.5 PASSIVE AND ACTIVE PROTECTION SYSTEMS

4.5.1 Procedure for passive protection against fire

Critical piping systems should have passive fire protection. However the application of PFP should be seen in the wider context of a safety plan for protection of piping against fires. The Norsok Procedure [70] reports such a plan which includes the following steps:

Step1. Identification of fire types and duration

The initial step is to decide on the characteristics of fire the pressure vessel/piping can be exposed to including the duration of the fire.

Step2. Effect of firewater

Water applied for controlling the fire and cooling of pressure vessels and piping is very effective when evenly distributed over the exposed areas.

Step3. Heat Flux values

Heat flux values for the next step are selected from **Error! Reference source not found.**.

Step 4. Depressurising/rupture calculations.

Perform depressurising calculations for each major pressure vessel and piping segment, establishing internal pressure fluctuation, wall material temperature and residual strength, as a function of time. Determine whether rupture will occur during depressurising, and identify time to rupture if this will occur.

Step 5. Evaluation of failure mode.

If a rupture of pressure vessels and piping occurs as a result of a combination of excessive heat load and internal pressure, an acceptance of the situation will have to be judged based on the risk analyses. Residual quantities and escalation potentials both within the area and towards adjacent areas shall be taken into account.

- Where rupture cannot be accepted, i.e. the risk acceptance criteria are not met, the provision of additional protective systems and arrangements shall be implemented. This can include one or more of the following options:
- Change from manual to automatic depressurising.
- Modifications to depressurising system (increase its capacity)
- Application of passive protection that will reduce the heat loads to the exposed pressure vessels/piping.
- Modifications to pressure vessel/piping design (material, wall thickness etc.).
- Modifications to the general arrangements that have an impact on the time to rupture.

The procedure will then have to be repeated from Step1, 2 or 3 as applicable.

Figure 49 shows how PFP can be used within the wider context of a safety plan for the piping system.

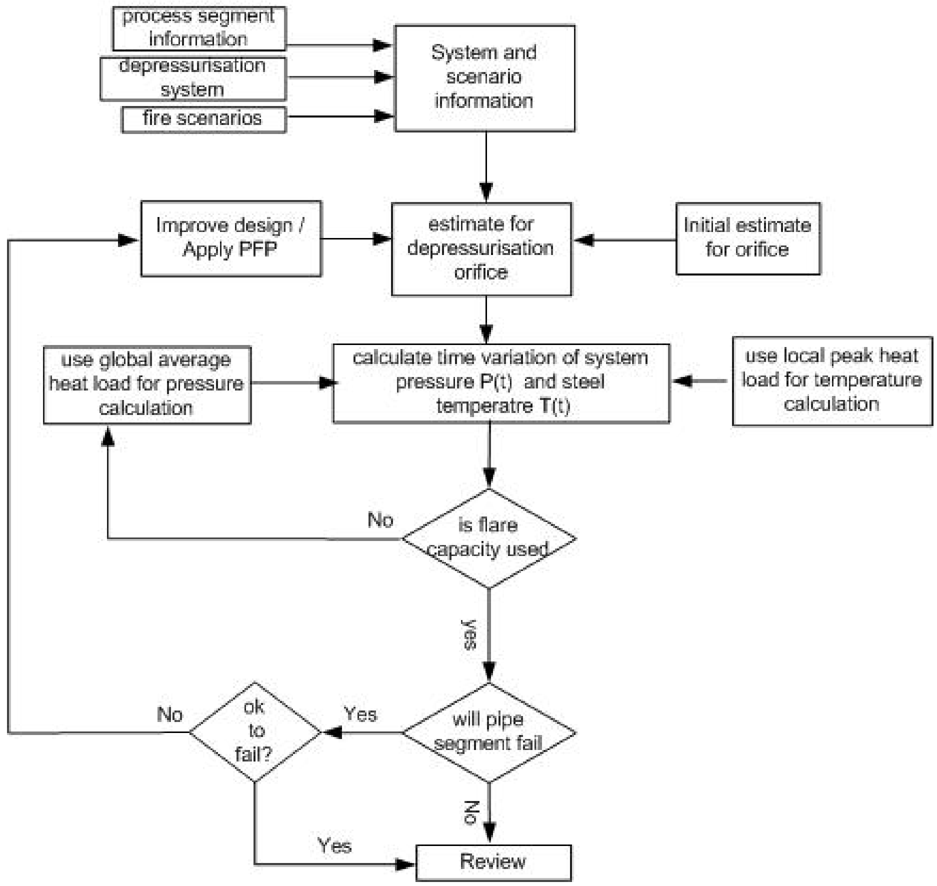


Figure 49 Passive fire protection with broader context of design of pressurised piping.

More recently, other procedures have been proposed by Scandpower [9] and the Institute of Petroleum [71].

4.5.2 Passive Fire Protection

Background

Passive fire protection (PFP) is defined, in the recently issued ISO standard 13702 (1999) [34], as "a coating, cladding or free-standing system which, in the event of a fire, will provide thermal protection to restrict the rate at which heat is transmitted to the object or area being protected". These materials are used to:

- prevent escalation of the fire due to progressive releases of inventory, by separating the different fire risk areas;
- protect essential safety items and critical components such as separators, risers and topside emergency shutdown valves;
- minimise damage by protecting the critical structural members, particularly those which support the temporary refuge, escape routes and critical equipment; and
- protect personnel until safe evacuation can take place.

The required fire resistance may be achieved by the use of PFP in conjunction with active fire protection systems such as water deluge, in which case a minimal residual protection must be achieved should the active systems fail to operate. PFP is used particularly where active systems are impracticable, have insufficient reliability or where protection is needed within the probable response time of an active system.

OTO 2000 051 [8] provides a very good background discussion on the use of PFP materials. Phase 1 of the Blast and Fire Engineering for Topside Structures project produced two reports relating to passive fire protection:

- *Passive fire protection: Performance requirements and test methods (Appendix A, OTI 92 606 [73])* which appraises the performance requirements for offshore PFP systems and assesses the adequacy of the then current tests for ensuring that performance; and
- *Availability and properties of passive and active fire protection systems (Appendix A, OTI 92 607 [74])* which reviews a selection of the various types of passive fire protection products which are used on offshore structures. Appendix C of OTI 92 607 [74] contains a listing of manufacturers, products and product properties.

The Interim Guidance Notes [2] give an indication of how the information given in these reports should be applied. After Phase 1, the areas of uncertainty were considered to be:

- Furnace-based fire tests do not relate to conditions in “real” fires and there was a requirement for fire tests with a manageable, reproducible, well-characterised flame which is used in conditions which can be related to those in a “real” fire;
- Smoke and toxic gas emissions need to be considered in the context of those from the primary fire;
- Requirements for robustness (e.g. tolerance to mechanical damage, explosion resistance)
- Ability to predict long-term durability were lacking; and
- Quality and maintenance were not given sufficient attention.

Chamberlain [75] provides a brief discussion on the recent findings from various JIPS related to the development of jetfire testing procedures for passive fire protection materials. These are reviewed in more detail in a later subsection.

Types of PFP

There are many types of PFP materials on the market, which can be broadly categorised into groups as follows [8]:

- Spray-applied and coating materials.
- Blanket / flexible jacket / wrap around systems.
- Prefabricated sections.
- Enclosures and casings.
- Composites.
- Seals and sealants.
- Fire walls.
- Systems (e.g. cable transits, inspection hatches, pipe penetration systems).

These are considered in greater detail by Roberts and Willoughby [76]. As weight is at a premium offshore, spray applied epoxy intumescent and subliming coatings are most frequently used now, although cementitious materials were extensively used in the past.

Functional requirements

In ISO 13702 (1999) [34], the following functional requirements are given:

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

PFP materials should be approved for their intended use. Various "approved lists" (see DNV [77] and LR [78]) exist which contain general data such as name and location of manufacturer, brief description of product, areas of application and type of certification. Where general approvals from a recognised third party or governmental body are not available, PFP fire performance should be documented by test reports from a recognised fire test laboratory. Jet fire resistance tests have been developed for this purpose as discussed in the following subsection.

Fire resistance tests

OTO 2000 051 [8] provides a very good review on test for passive fire protection material. Up to the early 1990's, most fire resistance tests were based on furnace tests in which a sample is exposed to a pre-determined heat-up regime whilst monitoring the thermal response on the reverse side of the sample. Originally, the heat-up regime used simulated cellulosic fires but then a hydrocarbon fire curve was developed to relate to hydrocarbon pool fires. The hydrocarbon curve has a steeper rate of temperature rise and a higher maximum temperature compared to the cellulosic fire curve.

It was generally recognised that the conditions in the standard hydrocarbon furnace test do not represent characteristics such as the balance of radiative and convective heat transfer, high gas velocities and thermal shock all of which are major factors with regard to the performance of passive fire protection in actual fires and in particular in jet fires resulting from high pressure gas leaks [75]. A key improvement has been development of the Jet Fire Resistance Test of Passive Fire Protection Materials (JFRT, OTI 95 634 [79]). This test involves use of a sonic, vapour-only 0.3 kg/s propane jet fire. The test was shown (OTO 97 079[80]) to reproduce key conditions typical of large scale fires resulting from high pressure releases of natural gas and is now widely used to assess PFP coatings and systems.

More recent work [81] has been carried out by the Health and Safety Laboratories which proposed a number of changes from the procedure originally developed and published by the HSE in [79]. These changes have been incorporated into a draft British Standard version of a test procedure for the determination of the resistance to jet fires of passive fire protection materials [82]. Following Roberts [81], the four versions of the original test, intended primarily for coating systems, are:

- Panel test that applies to cases involving panel material used to form the rear wall of the flame circulation chamber.
- Planar steelwork test used for PFP material applied to steelwork with no corners and edge features and to cylindrical vessels, pipes and tubular sections of outside diameter greater than 1.0m, and hence where the surface may be considered as planar.
- Structural steelwork test used for PFP material applied to steelwork with corners or edge features such as I beams.
- Tubular section test used for PFP materials applied to cylindrical vessels, pipes and tubular sections of up to 0.50 m outside diameter.

A key feature of the draft standard [82], as reported by [81], is the extension of the original procedure to cover the assessment of passive fire protection systems in an assembly test. A passive fire protection system is defined as [81] *a removable jacket or inspection panel, cable transit system, pipe penetration seal or other such system that, in the event of a fire, will provide thermal protection to restrict the rate at which heat is transmitted to the object or area being protected*.

The assembly test has so far been applied to:

- Cable transit systems,
- Pipe penetration seals,
- Removable ceramic fibre jackets
- Escape tunnel seal joints
- Inspection covers

The draft British Standard [82] addresses some of the key problems that are encountered in the test together with their influence on the validity of the test:

- Interruption of jet fire
- Failure of thermocouples
- Failure of a seal

The test is not intended to replace the hydrocarbon fire resistance test but is seen as a complementary test. In the jet fire test, the PFP will be subjected to erosive forces, pressure fluctuations and higher heat fluxes. However the highest erosive forces are not in the region of the highest heat flux and hence the results of both tests should be considered together when assessing the performance of a PFP material in a range of scenarios [81].

Prediction of PFP performance

OTO 2000 051 [8] provides a good review on the prediction of performance of PFP. In principle, the ability of a substrate to absorb heat is generally determined by its section factor or Hp/A ratio (alternatively referred to as A/V ratio); i.e. the heated perimeter (Hp, m) divided by the cross-sectional area (A, m^2). A substrate with a large mass and small surface area will take a longer time to reach critical temperature than one with a small mass and large surface area. Hence, in furnace tests, it is usual to vary the duration, section factor and thickness in order to provide an estimate of the thickness required in a range of situations. However, in a jet-fire resistance test, the heating is non-uniform and the measure of performance is the maximum temperature of the substrate. In the original JFRT, the substrate thickness used in the test should be as close as possible to the real application. The key performance criteria , provided by the test, is the minimum time required to reach the critical temperature associated with the fire scenario to be protected against.

A number of approaches have been used to predict the thickness of PFP material required. These include empirical and analytical techniques. Due to the complexity of the different situations, the fact that furnace testing can currently only be controlled by a time/temperature relationship (as opposed to a heat flux) and the limitations on the number of tests a manufacturer can reasonably be expected to perform, increasing use is being made of computer modelling. These consist of finite element analysis software for solving steady state or transient two dimensional, non-linear heat transfer equations. There are a number of such software available commercially. The use of CFD codes to predict heat fluxes to vessels or test specimens is becoming increasingly important. A recent example of using this technique to model the heat flux from the Jet-Fire Resistance Test is given in reference [83].

More recently, the draft British Standard [82], as reported by Roberts [81], includes a new section giving advice on additional factors to be considered when assessing performance. For coating and spray materials the following factors are considered:

- Substrate temperature, where the position and time of any sudden increase in the rate of temperature rise, is indicative of failure of PFP coating at that point.
- Reacted / un-reacted remaining material and condition of reinforcement.

For systems and assemblies, the corresponding considerations provided in the code [81] include:

- Substrate temperature
- Loss of integrity

Design and performance requirements

The new ISO 13702 (1999) [34] includes an Appendix C which gives typical fire integrity requirements. For example, for load bearing structures in process areas, resistance to a one hour jet fire at a critical temperature of 400°C is required. The JFRT is mentioned as a suitable test. The reference temperature of 400°C was used as a typical value for structural steel. For aluminum, the corresponding temperature is 200°C and, for other materials, the critical temperature is the temperature at which the yield stress is reduced to the minimum allowable strength under operating load conditions.

Recent articles have tried to address the issue of a risk-based Design Approach for passive fire protection (Yasseri, FABIG Article No. 2001 [84]).

Concerns related to use of PFP

- The main concerns relating to use of PFP include [9]:
- Increased corrosion of materials covered by PFP
- Performance of weathered PFP
- Reduced possibilities for inspection and maintenance of equipment covered with PFP

- Increased congestion
- Increased weight
- Increased need for space
- Increased need for maintenance of the PFP
- Increased cost.

Roberts [85] presented results of tests on PFP subjected to weathering and corrosion in the FABIG Technical Meeting on Passive Fire Protection. Initial conclusion included:

- Not too much temperature variation between weathered and new specimens
- Jet fire resistance test:
    1. Not too much temperature variation between weathered and new specimens
    2. Little difference in Char formation between weathered and new
    3. Large difference in Char formation at top and bottom positions
- Corrosion:
    1. All specimens showed some corrosion from edges
    2. some specimens heavily corroded
    3. method of application is critical

This means that PFP may lead to increased leak frequency and increased congestion. These factors do also lead to higher explosion risk, and it also means more personnel in the area, which again can be exposed to the accidents.

Specific concerns related to PFP on piping

While most guidelines for equipments are related to protection of vessels, it should be recognised that vessels and piping will behave differently in a fire situation due to different surface area to volume ratio [9]. The consequences of rupture would also be different for vessels and pipes. For pipes there is obviously a difference between gas filled and liquid filled lines. Due consideration should in this context be paid to "self draining" pipes, i.e. pipes that normally are completely or partially liquid filled could be dry in a shut down situation [9].

Specific concerns related to PFP on Flanges

As part of the Commission of the European Community (CEC) funded joint project on hazard consequences of Jet fire Interactions with **V**essels containing pressurised liquids [8], the Battelle Institute performed jet-flame impingement trials on unprotected and protected flange connections and found that:

- Typical LPG flange connections, and some new ones tested, do not resist jet fire attack;
- The time to loss of tightness depends on the intensity and position of the jet fire and can be as short as one minute;
- Standard API 92 and BSI 87 tests provide no real information about loss of tightness in a realistic jet-fire scenario; and
- New protective measures are required for jet fires.

4.5.3 Active Fire Protection

Background

The FABIG Technical Meeting on Mitigation [86] identifies the following main categories of active fire protection:

- Water deluge (general area, vessel specific, curtain, and hybrid)
- Foam systems
- Fire monitors for manual fire fighting

The primary form of fire protection to processing areas is water spray, where fixed deluge systems may be provided to:

- Control pool fires and thus reduce likelihood of escalation
- Provide cooling of equipment not impinged by jet fires
- Provide a means to apply foam to extinguish hydrocarbon pool fires
- Limit effects of fire to facilitate emergency evacuation, escape and rescue operations

OTO 2000 051 [8] identifies four broad types of deluge systems:

- Area protection designed to provide non-specific coverage of pipework and equipment within process areas
- Equipment protection designed to provide dedicated coverage of critical equipment such as vessels and wellheads
- Structural protection designed to provide dedicated coverage of structural members; and
- Water curtains to reduce thermal radiation

The Fire and Blast Engineering Project Phase II [3] investigated the effect of water deluge on confined pool and jet fires. The main findings were:

- The well ventilated jet fires were not extinguished by typical offshore water deluge. The jet fires continued to burn at the same rate but there was a substantial reduction in fire intensity.
- Fuel controlled (under-ventilated) jet fires were controlled but were not extinguished when deluge was activated soon after ignition.
- Fuel controlled (under ventilated) jet fires were extinguished when deluge was activated 10 to 12 minutes after ignition and the fire compartment was hot.
- There was no significant difference between the effects of water deluge on vertical and horizontal jet releases.
- It is possible for the fire to re-ignite after the water deluge is terminated due to the presence of hot gases and surfaces in contact with fuel.
- Extinguished jet fires represent a potential explosion hazard if the fuel continues to be released.
- Generally confined pool fires are not extinguished by water deluge, but the fire is controlled and burns at a much lower rate.

In a more recent Newsletter Article Shirvill and Lowesmith [87] reported on a major JIP study managed by Advantica. The main factors studied in the first phase include:

- The effect of water deluge coverage rate
- The effect of the size of the pool fires
- The effect of weather conditions
- An assessment of the differences between mitigating effects of sea and fresh water

The work showed that substantial work benefit may be gained particularly in reducing the thermal radiation field around a fire. In the case of pool fires, the deluge was also shown to reduce the size of the fire and, in certain circumstances, the interaction of the water with the pool lead to extinguishment. A further benefit was in the reduction in smoke levels within and beyond the rig.

The issues studied in the second phase of the work include:

- Stability of gas jet fires in the presence of deluge
- The effectiveness of deluge on condensate pool fire and crude oil jet fire
- The effectiveness of the spray generated by various nozzle types
- Vessels and pipe targets were included in the fires to allow an assessment of the ability of both area and dedicated deluge to provide protection to objects engulfed by pool or jet fires.

Design guidance

The Phase I Fire and Blast Joint Industry Project [1] refers to Department of Energy Guidance 'Offshore Installations: Guidance on Fire Fighting Equipment' Note SI 611. In this guidance, a general water application rate of 12.2 litres/min/m^2 is recommended.

The Interim Guidance Notes [2] quotes three additional rates:

- 10 litres/min/m^2 to protect against pool fires
- 20 litres/min/m^2 to protect against high pressure jet fires
- 400 litres/min/m^2 to protect against high pressure jet fires impinging on structural steelwork and vessels
- 400 litres/min/m^2 to each wellhead

OTO 2000 051 [8] presents a brief discussion on the application of water sprays for specific deluge on equipment. It is stated that the water spray design should surround the equipment with medium velocity nozzles spaced at 2.0 to 2.5 m intervals and 0.6 m from the surface. Complex-shaped objects would be covered by directing the spray at a virtual box enclosing the object under consideration.

Concerns related to use of Active Fire Protection

In the Technical Meeting on Mitigation, Renwick [86] identified various concern areas in the application of active fire protection. Most of these concerns are related to verification issues such as:

- Reliability of water supply

- Time to full activation
- Nozzle blockage
- Blast resistance
- Fire damage to dry Pipework
- Damage tolerance

In addition, the following special cases requires more attention:

- Impinging jet fire: deluge likely to be ineffective.
- Partially confined jet fires: deluge may be positively dangerous (extinguish flame and increase explosion risk).
- Wellbay / Xmas tree fires: very high water application rates often specified but purpose unclear.

4.6 TYPES OF PIPING AND MATERIAL PROPERTIES

There are no elevated temperature material properties data for the steel pipes used for carrying combustible fluids. For piping that does not convey combustible fluids elevated temperature material property data are available. However, they are based on isothermal or steady state test methods. In BS EN 10216-2 [60], BS EN 10217-2 [61] and BS 3604 [64], the data are minimum guaranteed 0.2% proof strength, whilst in BS 3605 [65], the data are minimum guaranteed values 1.0% proof strength. FABIG Technical Note 6 [7] provides data on elevated temperature properties for high strength steels used offshore. Selected parts of this data, relevant to offshore piping is used below.

4.6.1 Grades 1.4404 (316L) Stainless Steel

Determination of Young's Modulus at elevated temperature is extremely difficult since even the smallest inaccuracy in the measured stress-strain curves has a very significant influence on the modulus. Data from BS EN 10088 [88], Avesta Sheffield, Ugine, Thyssen and Inco are available. In addition to these data, recent work has been performed by Nordberg for Avesta Sheffield Research Foundation. Data from various sources have been analysed and the variation in strength factors at elevated temperatures are shown in Table 21.

Table 21 Stainless steel parameters of steel grade EN 1.4301

Temperature (°C)	$K_{E,\theta}$	$K_{0.2p,\theta}$	$k_{u,\theta}$	ε_u	$k_{2\%,\theta}$
20	1.00	1.00	1.00	0.40	0.26
100	0.96	0.82	0.87	0.40	0.24
200	0.92	0.68	0.77	0.40	0.19
300	0.88	0.64	0.73	0.40	0.19
400	0.84	0.60	0.72	0.40	0.19
500	0.80	0.54	0.67	0.40	0.19
600	0.76	0.49	0.58	0.35	0.22
700	0.71	0.40	0.43	0.30	0.26
800	0.63	0.27	0.27	0.20	0.35
900	0.45	0.14	0.15	0.20	0.38
1000	0.20	0.06	0.07	0.20	0.40

$k_{E,\theta}$ Young's modulus reduction factor E_θ/E
E_θ is the Young's modulus of steel of temperature θ,
$K_{0.2p,\theta}$ is the 0.2% proof strength factor $f_{0.2p,\theta}/f_{0.2p}$
$k_{u,\theta}$ is the ultimate tensile strength factor $f_{u,\theta}$ / f_u
$k_{2\%,\theta}$ is the 2% absolute strain strength parameter
$\varepsilon_{u,\theta}$ is the strain corresponding to the ultimate strength at temperature θ

4.6.2 Grade1.4462 (2205) Duplex Stainless Steel

Testing to determine the reduction of elastic modulus with temperature for grade 1.4462 (2205) stainless steel was performed by RWTH. Data is also available from a research report produced by Ugine. However, in this case data is limited to temperatures up to 300°C. The data shows that this grade of duplex steel does not retain it elastic modulus as well as austenitic stainless steels at temperatures above 500°C. Elevated temperature material properties data for grade 1.4462 (2205) duplex steel are available from a number of sources.

Transient state tests have recently been performed by RWTH for the SCI ECCS project for Grade 1.4462 (2205) duplex steel. A summary of the data consisting of strength factors at various strains for temperatures up to 1000°C are presented in Table 22.

Table 22 Stainless steel parameters of steel grade EN 1.4462

Temperature (°C)	$k_{E,\theta}$	$k_{0.2p,\theta}$	$k_{u,\theta}$	ε_u	$k_{2\%,\theta}$
20	1.00	1.00	1.00	0.20	0.35
100	0.96	0.91	0.93	0.20	0.35
200	0.92	0.80	0.85	0.20	0.32
300	0.88	0.75	0.83	0.20	0.30
400	0.84	0.72	0.82	0.20	0.28
500	0.80	0.65	0.71	0.20	0.30
600	0.76	0.56	0.58	0.20	0.33
700	0.71	0.37	0.38	0.15	0.40
800	0.63	0.26	0.29	0.15	0.41
900	0.45	0.10	0.12	0.15	0.45
1000	0.20	0.03	0.04	0.15	0.47

4.6.3 Grade 1.4362 (SAF 2304) Duplex Stainless Steel

No elevated temperature material properties data is available in Standards. Limited data is available from stainless steel manufacturer Avesta Sheffield. The data was used to generate strength retention factors to be used with the stainless steel model. The strength reduction factors are given in **Error! Reference source not found.**.

Table 23 Stainless steel Parameters of steel grade EN 1.4362

Temperature (°C)	$k_{E,\theta}$	$k_{0.2p,\theta}$	$k_{u,\theta}$	ε_u	$k_{2\%,\theta}$
20	1	1	1	0.2	0.35
50		0.902893	0.94898	0.33	
100	0.96	0.820248	0.865889	0.33	0.35
150		0.760331	0.819242	0.34	
200	0.92	0.681818	0.7781341	0.3	0.32
250		0.665289	0.774052	0.33	
300	0.88	0.632231	0.776968	0.29	0.3
400	0.84	0.605372	0.744898	0.26	0.28
450		0.683884	0.760933	0.33	
500	0.80	0.609504	0.682261	0.33	0.3
550		0.456612	0.524781	0.33	
600	0.76	0.36157	0.440233	0.43	0.33
650		0.316116	0.40379	0.33	
700	0.71	0.25	0.327988	0.5	0.4
750		0.183884	0.196793		
800	0.63	0.14876	0.163265		0.41
900	0.45	0.065083	0.09621		0.45
1000	0.20	0.024587	0.05102		0.47
1100		0.008884	0.027697		

4.6.4 Summary of Available Data

Table 4.6 below provides a summary of available material mechanical properties at elevated temperatures for the commonly used offshore steels. Further research and experimental tests may be required to generate the missing data, marked with a ✗, in the Table below.

Table 24 Availability of elevated temperature material property data

Steel Property	316L	X52/X65 (API 5L)	A333 Grades 3, 6	Duplex	GRE	Copper -Nickle
Modulus of Elasticity, E_{θ}[i]	✓	✗	✗	✓	✗	✗
Poisons ratio, ν_{θ}[ii]	✓	✗	✗	✓	✗	✗
UYS, $\sigma_{y\theta}$[iv]	✓	✗	✗	✓	✗	✗
ULS[v]	✓	✗	✗	✓	✗	✗
UTS[vi]	✓	✗	✗	✓	✗	✗
Rupture Strain, ε_u[viii]	✓	✗	✗	✓	✗	✗
Stress-Strain curves[ix]	✓	✗	✗	✓	✗	✗
Notes: i. It is assumed that Poisson’s ratio remain constant with temperature variation						

4.7 DESIGN OF PIPING UNDER FIRE

Process plant and pipework have a much broader spectrum of response to fires than structures. The performance ranges from the simple sagging of a dry pipe to the possible catastrophic explosion of a pressure vessel or a hydrocarbon-transporting pipe.

4.7.1 General

The resistance of pipework to fire loadings is extremely variable. The main considerations are:

- Insulation: If a process line is partially or completely insulated for process reasons, it may perform well under fire loads, but some lagging materials are unlikely to be effective in a fire.
- The size of the pipework.
- Material of construction: The prime material types are carbon steel, lined carbon steel, stainless steel and Kunifer. These materials have different elevated temperature characteristics, and will behave differently under fire loading conditions. The material properties will be linked to a function of the pipe itself and so evaluation should be carried out on a system-by-system basis.
- Contents and Flow-Rate: The normal contents of the pipe will need to be considered. The internal pipe fluid will be able to remove local heating at a rate which will be determined by the properties of the fluid itself and the fluid flow-rate. Gases will have little cooling effect, whilst water will give considerable assistance.

4.7.2 Acceptance Criteria

It is necessary to define criteria which can be used to assess the performance of piping systems under fire conditions. The main acceptance criteria for piping systems may be categorised under three broad categories, also used for the structural components:

- strength limit
- strain limit
- deformation limit
- maintenance of structural and insulation integrity.

Strength limit

Where strength governs design, failure is defined as occurring when the design load or load effects, exceed the design strength in a manner that is similar to conventional design. The principal difference for fire resistant design is that modified factors on loading and/or strength may be adopted as it is an extreme event and the strength assessment must take account of the changes of mechanical properties with temperature.

Strain limit

The following criteria should be considered when determining the strain limit to be used in design:

- Material contained within the piping system
- Cross-sectional geometry and proportions
- The deformation capacity of any protection material present.

Displacement limit

The following criteria should be considered when determining the strain limit to be used in design:

- Type of attachment (in terms of ductility) between piping and other equipment
- Type of support condition for piping system (whether it may be subjected to opposing displacements from support points)

4.7.3 Design Methods

The following design methods may be used for the design of piping against fires:

Zone Method

The main philosophy of the zone method is to divide the platform into areas with predetermined design standards. Hazardous area classification zones are used in topsides design to trigger standard details for a number of fittings, items of equipment and design philosophy. The platform is divided into zones and fire areas. As a natural extension of this, fire design is considered for the individual zones already created. For example, passive fire protection may be specified on all hazardous piping in the higher part of the 'hazardous' (Zone 1 and Zone 2) module, with thicknesses being determined using techniques such as the section factor (Hp/A) method. This approach treats each zone as a 'fire compartment', a concept which has been borrowed from onshore practice, which inhibits the broader consideration of realistic fire situations.

Also included in this category is the notion of 'simple inspection'. By inspection of the engineering drawings (usually involving some concept of zoning), those structural elements that 'appear' to be most likely to prevent structural failure are selected for passive fire-proofing.

Limiting Temperature Method

This is the traditional approach to fire design. It assumes that structural failure occurs when the steel reaches a critical temperature, usually about 400 - 500ºC. At this temperature the steel exhibits an approximately 50% reduction in yield stress. This corresponds to the likely working stress level in the member. Note that allowing an overstress of 1.7 in allowable stress design is directly equivalent to reducing the yield stress by 42%. This assumes that the effect of stresses induced by thermal restraint can be ignored

All steelwork requiring a pre-defined fire resistant period (say one or two hours) is uniformly protected with PFP such that the temperature does not rise above the specified temperature limit of 400 ºC during this time. No account is taken of the load level in the member at the time of the fire.

Code Check Methods

Code check methods based on the use of existing ambient temperature structural design codes can be used to determine if hot steel structural components satisfy the specified code unity check. The procedure is as follows:

- Carry out a room temperature linear elastic analysis to determine member forces and unity checks for each member.

- Incorporate the modified (reduced) safety factors into the code check. This will decrease the unity check. This procedure will be different for allowable stress design compared to limit state design:
    - Allowable stresses: two methods are available. The first is to increase the allowable stresses to an appropriate value for fire loading, for example by increasing the denominator of the unity check.
    - Limit state: in limit state design, the safety factors are applied directly to the loads and material properties. It is therefore a straightforward process to reduce these to the values applicable for the fire limit state (i.e. reduce the numerator of the unity check).
- Adjust the yield strength and Young's Modulus to correspond to the properties at the anticipated temperature of each member. This will lead to a reduction in the denominator of the unity check and hence increase its value.
- Assess whether the final modified unity check is satisfactory (less than 1).

However, a number of limitations still exist with this approach:

- In slender compression members a combination of thermal stresses with the applied loads may lead to premature failure. In such instances, code methods may be unconservative.
- It can be difficult to modify allowable stress codes.
- Most codes are not validated at elevated temperatures.

4.7.4 Stress Calculation Methods

When assessing the strength limit acceptance criteria, the stresses in the piping are calculated and compared against the strength of the pipe allowing for strength degradation due to fire.

The stress on the piping system consists of contribution from various loads including:

- Self weight
- Hydrostatic pressure of fluid contained in pipe
- Internal fluid operating pressure
- Weight imposed by flanges and valves
- Thermal expansion
- Boundary constraints

The need for simplified methods arises during the design of piping systems for depressurisation, a procedure described in Section 4.5.1, where Task 4 shows that shows the failure / rupture calculations need to be carried out well before the final design layout has been arrived at.

Simplified methods for the analysis of piping are considered to give good results for process piping systems where the internal pressure is high [9]. For elements with low pressure, or for elements where components other than internal pressure are expected to have a significant contribution to the total stress, the validity of these simplified methods become more uncertain.

In addition even for cases where internal pressure is the most significant component contributing to the total stress, it is considered important to carry out a finite element analysis for verification purposes [9].

This section provides a brief discussion on simplified methods and finite element analysis methods as applied to the analysis of piping systems under fire.

Approximate analytical Methods

According to design code for piping, ASME B31.3 [33], as reported by the recent guidance issued by Scandpower [9], the main stresses in a piping system are:

- The "hoop stress" due to internal pressure
- The "longitudinal stress" either caused by sustained or displacement loads.

The hoop and the longitudinal stress can be calculated from the following equations:

Hoop stress: $$\sigma_{\text{hoop}}(t) = \frac{\left(p(t)\cdot OD\right)}{2\cdot wt} \qquad (1)$$

Longitudinal stress: $$\sigma_{\text{axial}}(t) = \frac{\left(p(t)\cdot OD\right)}{4\cdot wt} + \sigma_{\text{ext}} + \sigma_{\text{displ}} \qquad (2)$$

Equivalent stress: $$\sigma_{\text{Von-Mises}} = \sqrt{\sigma_{\text{hoop}}^{2} + \sigma_{\text{axial}}^{2} - \sigma_{\text{hoop}}\cdot\sigma_{\text{axial}} + 3\tau^{2}} \qquad (3)$$

Where:

$\sigma_{\text{hoop}}(t)$: Time dependent hoop stress.
$\sigma_{\text{hoop}}(t)$: Time dependent axial stress.
p(t): Time dependent internal pressure.
OD: Outer diameter of pipe.
wt: Wall thickness of pipe.
σ_{ext}: Longitudinal stress due to external loads.
σ_{displ}: Longitudinal stress due to thermal expansion and support constraints.
τ is the shear stress due to torsional stresses that may arise from the slide / guide support systems

Notes on the use of the Scandpower method:

- Constant stress across the thickness is assumed, which is valid for thin walled pipes but for thick walled pipes becomes conservative.
- Normally the thermal expansion can be neglected. In some situations, thermal expansion can cause big moments in the piping system and in the flanges of bolted connections, which in turn may lead to leaks. These leaks will probably be reduced or totally disappear when the piping system starts to yield, hence the reason for neglecting the thermal stress. However, it must be considered whether such leakages are acceptable. However, in stiff piping geometries special considerations have to be made.

Non-Linear Finite Element Analysis

Non-linear finite element analysis permits the rupture calculations of a piping system to be based on more accurate methods which accounts for the reserve strength inherent in many design codes. It also overcomes the approximations that have been identified with the use of simplified methods.

4.8 OUTSTANDING ISSUES

The following outstanding issues should be addressed:

- Although property data at ambient temperature are available, high and low temperature data are not available for some of the steels. Low temperature data are required if excessive cooling occurs during emergency depressurisation and high temperature data are required if the system is to be designed to withstand a significant fire loading.
- The effect of plastic deformation will be particularly noticeable if the pipe has locally high stresses, or equivalently, local regions of low strength. Thus, the effect of a fully engulfing pool fire will be very different from that of localised fire engulfment. Little quantitative information is available as to the effect of this, and as a consequence, stress is usually calculated on the basis of elastic behaviour.
- Little information exists on the performance of pressure relief devices under fire engulfment conditions. Although standard tests exist for isolation valves engulfed in fire, there are no analogous tests for pressure relief devices. Such tests need to be developed to ensure that the devices will operate in a satisfactory manner under fire loading.
- The evidence suggests that vessels operating at modest pressures are most vulnerable due to their thinner walls. The walls of very high pressure vessels provide such a large thermal mass that even severe fires should not cause the shell of the vessel to fail. No similar work has been carried out on piping systems.
- Flanged connections to vessels are known to be particularly vulnerable to non-uniform heating from a jet fire and severe leakage may be as important as vessel rupture. The evidence suggests further work is required to assess the resistance of flange connections to jet-fire attack. No similar work has been carried out on piping systems.
- It is clear from the study that insufficient suitable information exists at present to allow engineers to carry out design calculations on any steel other than the common structural steels. To design adequately or analyse a structure for fire, stress-strain curves for steel are required for strains up to at least 5% and for temperatures up to 700 ºC – 800 ºC maximum. This information is only available for the most common structural steels in the Eurocodes.
- The available data is generally limited to 0.2% proof stress values and needs extending to full stress-strain curves. The basis on which the data is quoted, Average or Minimum Guaranteed values, needs unifying such that meaningful comparisons can be made. Ideally, the test that were carried out to obtain the Eurocode steel properties data should be repeated for all the types of steel that may be required to be designed/analysed to take into account elevated temperatures. Having gained the knowledge in deriving that data, it should be possible to use a shortened test programme for many of the steels.
- Before steels with enhanced properties at elevated temperature (‘fire-resistant’ steels) can be confidently used, further investigation from both the elevated temperature properties standpoint and the low temperature impact properties standpoint must be made. In addition, although beyond the scope of this Project, the economics of using these ‘fire-resistant’ steels needs to be studied.

5 RESPONSE OF PIPE SUPPORTS TO FIRES AND EXPLOSIONS

5.1 INTRODUCTION

This chapter considers the techniques that may be used in the design of piping supports against fires and explosions. Piping supports may be divided into the following broad categories:

- Welds and bolts that attach the piping systems to various support configurations
- The steel that comprises various supports layouts
- Secondary steelwork that support various support configurations.
- Bolted connections of the pipework system such as flanges and valves.

Pipe supports are used to support the weight of piping runs, the associated valves and the contained fluids. Pressurised piping systems that contain fluid, particularly gas, are likely to have a low weight per unit length of pipe compared to the pipe self-weight. The pipe supports play a key role in the maintenance of integrity of the piping system. Valves, joints and other piping fittings can rupture or leak if subjected to large strains, which could develop if one or a number of pipe supports were to fail. It is normal practice for piping containing hydrocarbons in hazardous areas to be joined by welding wherever possible.

In some cases the pipe supports have a multi-purpose function and support a number of different services. For example, cable ladders and HVAC ductwork may be supported along with piping.

The recent trend has been to use “multi-discipline” supports for major pipe racks, which will also support electrical and instrument cables; this concentration of services may present a greater hazard in a local fire, but should be easier to provide total protection.

Section 5.2 presents a review of the main support types used on offshore platform, with emphasis on supports that do not contribute to relative displacements. Section 5.3 discussed the behaviour of supports under fire conditions, while section 5.4 present guidelines for the protection of supports under explosions.

5.2 TYPE OF PIPING SUPPORTS

The support types that are commonly used as guides and anchors for piping systems include:

- Trunion Base Plate with support and slide guide units;
- Trunion Base Plate with support and stop slide units;
- Trunion Base Plate with support, guide and stop slide units;
- Adjustable Trunion Base Plate (Bottom Plate only);
- 4 Bolt clamps for Copper-Nickel Lines 8 Inches and above;
- 3 Bolt Clamps for S S, Duplex, Galvanised and Acoustic Insulated lines;
- Lateral support without vertical restraint.

Figures 5.1 to 5.7 show the main support types listed above. The most robust support type is type 7 which provides lateral restraints to large pipes, without imposing any vertical displacement due to roof deformation under blast conditions.

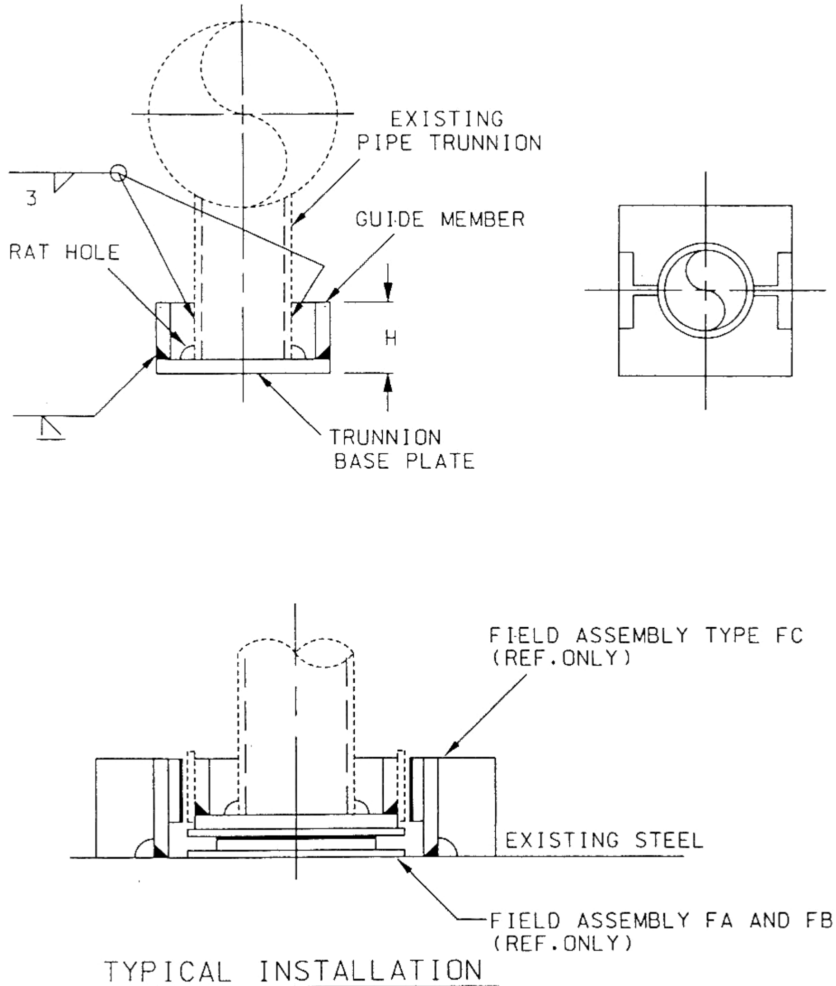


Figure 50 Type 1*:* Trunion Base Plate with support and slide guide units

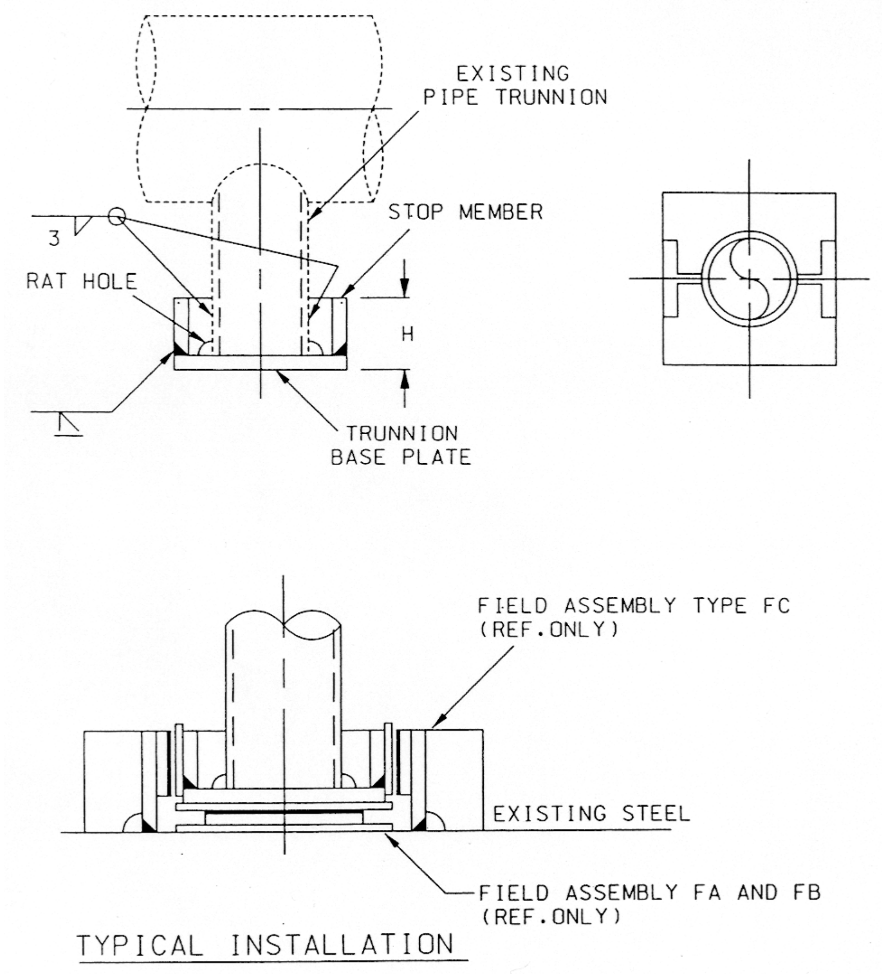


Figure 51 Type 2:Trunion Base Plate with support and stop slide units

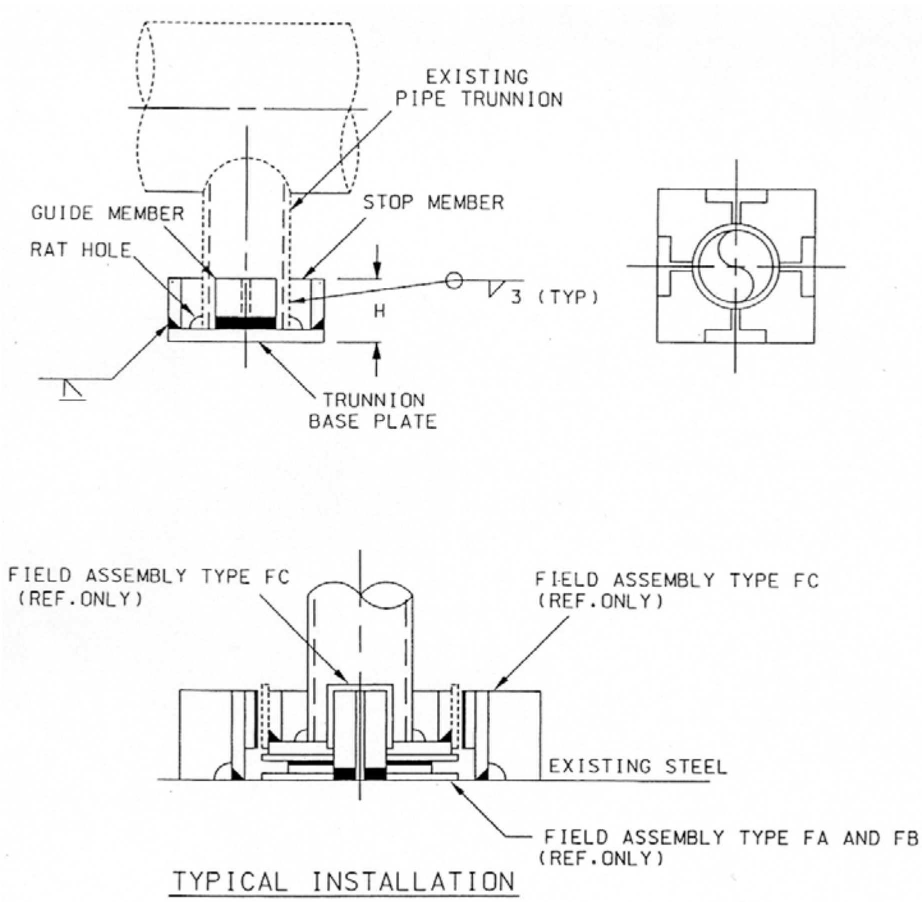


Figure 52 Type 3: Trunion Base Plate with support, guide and stop slide units

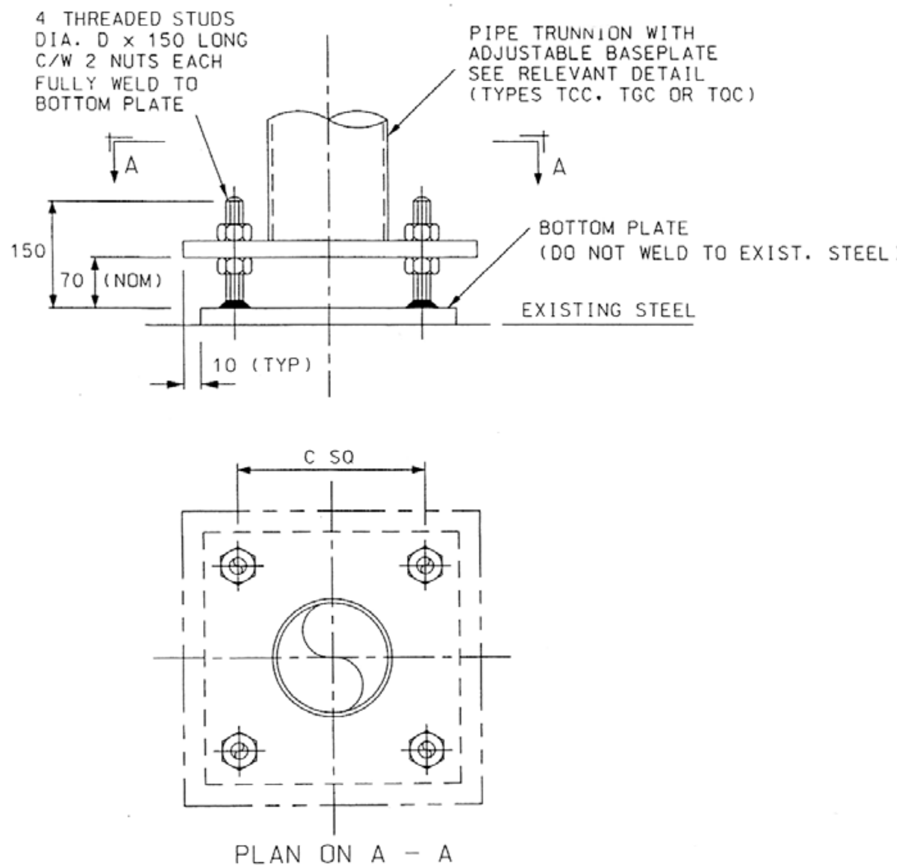


Figure 53 *Type 4:* Adjustable Trunion Base Plate (Bottom Plate only)

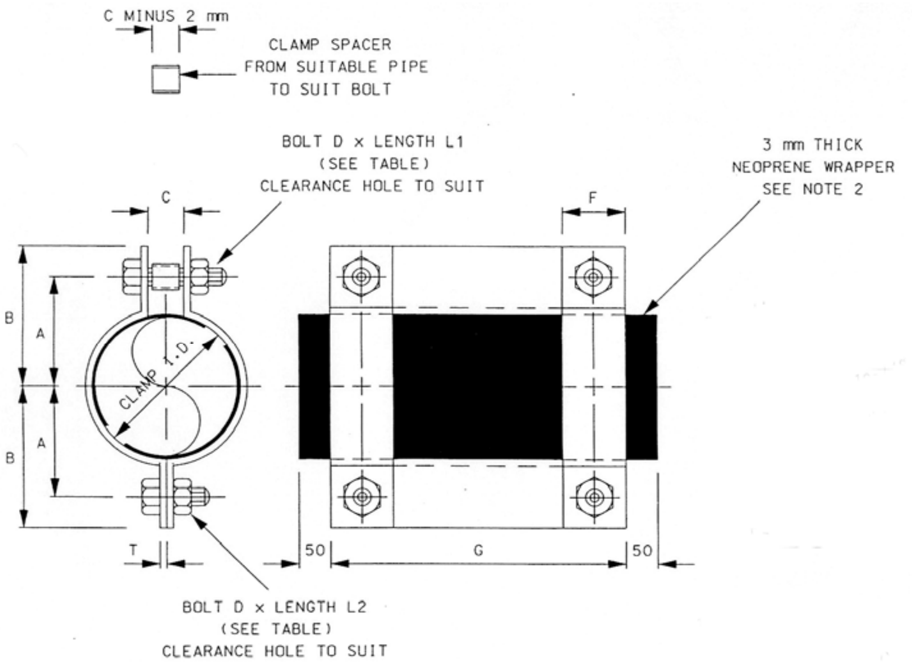


Figure 54 Type 5: 4 Bolt clamps for Copper-Nickel Lines 8 Inches and above

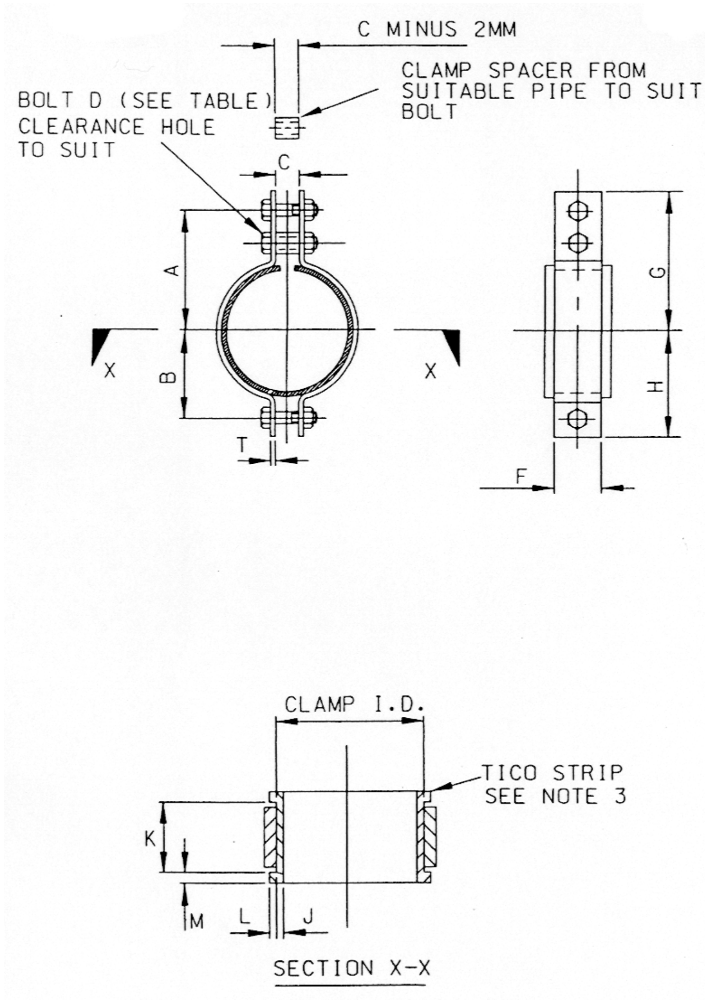


Figure 55 Type 6: 3 Bolt Clamps for S S, Duplex, Galvanised and Acoustic Insulated lines

Figure 56 Type 7: Lateral support without vertical restraint

5.3 DESIGN OF PIPING SUPPORTS TO RESIST FIRES

Bolted fittings themselves will need to be examined as their performance in a fire could be short-lived (if a bolt is under tension at ambient temperatures then it will go slack if heated). Sealing devices in valves may break down at elevated temperatures.

Pipework fluids may play a role in cooling their supports in a fire, but in many cases this potential cannot be realised because the heat path cross-sectional area is relatively small at the junction of the two elements.

The new guidance on the protection of pressurised systems recommends that the pipe/equipment supports, and the secondary steel supporting these supports, must keep their integrity until it is acceptable for the equipment/pipe they support to rupture. For this reason, the supports have to be protected by use of PFP unless total integrity can be documented by analyses. If for any reason it is desired not to use PFP on all the pipe supports, it must be documented that the pipe integrity will be kept without the presence of PFP on all pipe supports.

5.3.1 Specific guidance on bolts and welds

The recommendations for welds and bolts are drawn from [89] which is based on BS5950 Part 8 [90].

It is generally accepted that welds behave in a manner similar to the parent material in fires. However, there is some conflicting evidence that suggests a significant reduction in weld strength after a fire. However, the failure mode associated with the fire is not known, neither is the actual condition of the weld before the fire.

Bolts do not behave very well in fires, and the higher the bolt specification, the poorer the fire enduring qualities. The loss of strength of Grade 4.6 bolts follows that of Grade 43 steel. For

Grade 8.8 bolts, the strength reduces after exposure to temperatures above 450ºC, being 80% at 600ºC and 60% at 800ºC.

High strength friction grip bolts behave in a similar manner to Grade 8.8 bolts.

Higher specification bolts such as ‘L7’ and those formed from ‘Macalloy’ bars, etc., should be replaced as a matter of routine if fire damage has occurred. Alternatively, advice should be sought from the material suppliers. Note that nickel-based alloys may maintain good mechanical properties both during and after a fire.

The Scandpower guidance provides the following additional information on the behaviour of bolts:

- Bolted connections, including flanges and valve connections, must be verified with respect to the need for fire protection. The bolts will not obtain any cooling from the fluid inside the pipes.
- All bolted connections are pretensioned. As the bolts are made of high strength steel they usually lose their pretension, and soften at a temperature lower than the piping yield temperature. This may lead to leakage even at stress levels lower than the strength level.
- The temperature in the bolts must be kept below 500ºC.
- Unless connections are specifically designed to withstand higher temperatures, PFP shall be used for the connections.

5.3.2 Flange connections

Reference [1] describes experiments to determine the thermal response of flange connections, the time to loss of tightness and failure modes during jet-fire attack. The tests established that the tightness of a flange connection may be lost and new leaks formed between 1 and 8 minutes after the start of the fire. An asymmetric temperature distribution develops in the flange connection even in an engulfing jet flame, the downstream side of the flange being hotter. The loss of tightness was attributed, in all cases, to the same cause viz: the decrease of the contact pressure because the temperature induced expansion of flange bolts was higher than that of the flanges. Moreover, because of the thermal gradient in the flange connections, the bolts elongate differently and the leaks occur in the areas with higher temperature. It was concluded from this work that:

- Standard tests according to API and British Standards provide no real information on the loss of tightness in real fire scenarios of jet-fire impingement;
- in the tests, the elongation of the bolts remained in the elastic range;
- the sealings showed little or no damage and, after cooling down at the end of the tests, some test samples even re-gained their tightness; and
- in a real fire case, the loss of tightness would lead to damage of the sealings as the leaks would ignite.

5.3.3 System Steelwork

System steelwork is used to form and hold up the process system. The fire design requirement for system steelwork is simply to ensure that failure does not promote the escalation of fire. With pressurised piping systems the contained fluid, particularly if a gas, is likely to have a low weight per unit length of pipe compared to the pipe self-weight. The pipe supports play a key role in the maintenance of integrity of the pipework system. Valves, joints and other pipework fittings can rupture or leak if subjected to large strains, which could develop if one or a number of pipe supports were to fail. Bolted fittings themselves will need to be examined, as their performance in a fire could possibly be short-lived (if a bolt is under tension at ambient temperatures then it will go slack if heated). Sealing devices in valves may break down at elevated temperatures. The effect of fire on system steelwork can be assessed using methods described in Chapter Four.

5.4 DESIGN OF PIPING SUPPORT TO RESIST EXPLOSIONS

In addition to the guidelines provided in section 3 for the protection of piping systems against explosions, the most important point for piping supports is to ensure that the pipe will not be subjected to large forces due to relative displacement at the supports. This can be ensured by using supports that will separate from the pipe rather than supports that will pull the pipe in conjunction with them as they deform. Support type 7 illustrates this point.

Loads acting on supports consisting of secondary beams and other steelwork, and the corresponding response of such items, may be determined in the manner described by the Interim Guidance Notes and subsequent technical notes.

5.4.1 Specific guidance on bolts and welds

Welds and bolts are loaded indirectly as they transfer the forces generated by an explosion from one member to another. The significant characteristics of these forces are that they occur rapidly and are large in magnitude.

Welds normally have mechanical properties similar to or better than the steelwork to which they are attached. However, there is a greater variation in properties than for rolled steel and consequently “bad” zones can exist. These are particularly prevalent in the parent metal immediately adjacent to the weld (the heat affected zone). The result can be that small defects lead to brittle failure under rapid loading. In general, these problems are completely avoided by suitable detailing and correct welding procedures.

Provided bolts are sized to take the explosion-related load, there should be no problem with regard to premature failure. Where loads exceed the design value, bolts will either fail in brittle fracture or by plastic deformation. The higher the grade of bolt used, the more likelihood there is of brittle fracture. Bolts used offshore are usually Grade 4.6 or Grade 8.8 which should not be prone to brittle failure.

5.4.2 Fittings and Flange Connections

- In practice piping incorporates flanges and possible other fittings which are not as strong in bending as the pipes to which they are welded, and these will fail in a largely brittle manner before the yielding capacity of the pipe is reached. Unless this can be avoided (for example, by using a higher class of flange), the ductility of the pipe itself cannot be assumed to reduce the load applied to the pipe. In other words, piping made of a ductile material, cannot be assumed to be ductile unless the whole piping system has been designed to behave in a ductile manner.
- Elbows, tees and nozzles must either be inherently ductile themselves or be stronger than the piping. This can be checked by component tests or nonlinear finite element analysis.
- Predicting the ductile capacity of fittings and connections is difficult and many items will incorporate features and connections that have no ductile capacity at all.

5.4.3 System Steelwork

In the case of both fires and explosions, ductility of the supports becomes a very important requirement to ensure that the pipe can deform plastically without failing.

5.4.4 Guidelines for ductile construction

The types of piping supports reviewed in Section 5.2 may be subdivided into two broad categories:

- Base Plate type connections
- Hanger type connections

Both types of connection consist of bolts and steel components (plates or rods). In both cases, to ensure a ductile failure mode, the capacity of the bolts should be greater than the plastic moment of the attached plate or rod. The plastic capacity of the plate or rod should be an upper bound value taking account of yield variation and strain rates.

Particular care should be taken to ensure that the steel connections can withstand both the dynamic loads and any load reversals imposed on them. The parameters that may be varied to ensure that plate / rod failure will occur before bolt failure are:

- Bolt spacing
- Thickness of plate / rod
- Shape of stress strain curve of material

5.5 OUTSTANDING ISSUES

- Little information, relating to the elevated temperature properties of welds or bolts, is available. The yield-strength reduction factors for welds and bolts are given in BS 5950: Part 8 [90]. Phase I reports [1] states that bolts do not behave very well in fires, and the higher the bolt specification, the poorer the fire enduring qualities. The loss of strength of Grade 4.6 bolts follows that of Grade 43 steel. For 8.8 bolts, the strength reduces after exposure to temperatures above 450 ºC, being 80% at 600 ºC and 60% at 800 ºC.

- There is a conflict in the literature about the way in which welds behave in fire conditions [1]. A study carried out by the Department of Energy examined some fire-damaged tubular elements and concluded that the fire had reduced the basic strength of the welds, whereas BS 5950-8 suggests no change in performance after the cooling down period for the commonly used structural steels. Tests should be made on the strength of fire-damaged welds, taking into account the typical processes and details in use for offshore construction.

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