Scandpower
Risk Management AS

Guidelines for the Protection of Pressurised Systems Exposed to Fire

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Client Hydro and Statoil

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Title:

GUIDELINES FOR THE PROTECTION OF PRESSURISED SYSTEMS EXPOSED TO FIRE

Client: Hydro and Statoil

Client specification:

Establish guidelines for the protection of pressurised systems exposed to fire. Maintain and update the document in co-operation with Statoil and Hydro

Summary:

These guidelines define the principles and a methodology that may be adopted for the design, construction and operation of systems and arrangements for fire protection of pressurised process piping and equipment.

These guidelines are valid for on- and offshore process facilities.

These guidelines are developed in line with the principles outlined in ISO 13702 and hence, also represent an important contribution to the establishment of a Fire and Explosion Strategy, FES, for the plants in question.

The content of these guidelines is divided into three main parts.

The first part (Chapter 3) presents, in general, the main principles of fire protection of process systems.

The second part (Chapter 4) presents and discusses the main parameters to consider in a fire protection strategy for a process facility.

The third part (Chapter 5) presents a more specific procedure for how to arrive at an optimum protection scheme with respect to fire protection of process systems

Key words	Name		Signature
Guidelines Pressurised System Fire Protection Depressurisation Passive Fire Protection	**Prepared by:**	Bjørn Hekkelstrand Paul Skulstad	Paul Skulstad
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1. INTRODUCTION

These guidelines define the principles and a methodology that may be adopted for the design, construction and operation of systems and arrangements for fire protection of pressurised process piping and equipment.

These guidelines are valid for on- and offshore process facilities.

The guidelines are developed in line with the principles outlined in ISO 13702, Ref. /1/, and hence, also represents an important contribution to the establishment of a Fire and Explosion Strategy, FES, for the plants in question.

The main principles of and major input to this document is taken from Hydro’s "Best Practice Depressurisation and Fire Relief Design", Ref. /2/.

These guidelines should be used throughout the conceptual, basic and detailed engineering stages of new plants. The guidelines should also be used for modification projects of existing plants. When key operational parameters affecting the fire safety are to be modified on an existing plant, the principles in the guidelines should be applied. It is important to use these guidelines as early as possible in a project development.

The availability of information or data is increasing through a project's lifetime. This will to some extent affect the analysis in the way that the need for safety margins will be higher when the data is less accurate or even not available, e.g. in the early phase of a new project. The guidelines aim to give guidance to a sound and safe approach in these cases.

The objective of these guidelines is to achieve a safe and cost efficient design of pressurised systems that may be exposed to fire. This means a focus on fast depressurisation instead of using passive fire protection (PFP). PFP is considered as an effective measure that reduces the consequences of a fire. However, PFP also introduces problems relating to corrosion and ultimately possible hydrocarbon leaks, reduced possibilities for inspection, space and cost. The guidelines direct the design to take full advantage of other measures such as proper material selection, pressure rating, wall thickness etc. that may reduce the need for PFP. The guidelines provides a procedure that may be applied and supporting background information pertaining to hydrocarbon fire characteristics (Appendix A) and material data and failure criteria (Appendix B/C).

The content of the guidelines is divided into three main parts.

The first part (Chapter 3) presents, in general, the main principles of fire protection of process systems.

The second part (Chapter 4) presents and discusses the main parameters to consider in a fire protection strategy for a process facility.

The third part (Chapter 5) presents a more specific procedure for how to arrive at an optimum protection scheme with respect to fire protection of process systems.

The application of this procedure is considered to result in adequate protection against realistic fires. A supplement to the procedure is to use a risk-based approach for the fire scenarios, the heat loads and acceptance criteria for rupture. It must be documented that the chosen solution is the safest or at least within the risk acceptance criteria. This possibility is not followed any further in this version of the guidelines.

New knowledge shall be implemented in the guidelines whenever it is documented that such new knowledge will improve the results. All projects using the guidelines are requested to fill in and submit the experience feedback form included in this guidelines (see Appendix D).

The responsible party for updating and maintaining the guidelines is Scandpower Risk Management AS in close co-operation with Hydro and Statoil.

2. DEFINITIONS AND ABBREVIATIONS

2.1 Abbreviations

AFP: Active Fire Protection
ALARP: As Low As Reasonable Practicable
API: American Petroleum Institute
ATS: Allowable Tensile Strength
BDV: Blowdown Valve or Depressurisation Valve
CFD: Computational Fluid Dynamics
DAL: Design Accidental Load Specification
ESD: Emergency Shut Down
FES: Fire and Explosion Strategy
F&G: Fire and Gas
J/T: Joule Thompson Effect
LNG: Liquefied Natural Gas
LPG: Liquefied Petroleum Gas
NPD: Norwegian Petroleum Directorate
NDT: Non Destructive Testing
PAH: Pressure Alarm High
PAHH: Pressure Alarm High High (shut down pressure)
PCV: Pressure Control Valve
PFP: Passive Fire Protection
PSA: Petroleum Safety Authority Norway (former part of NPD)
PSD: Process Shut Down
PSV: Pressure Safety Valve
PV: Pressure Control Valve
QRA: Quantitative Risk Analysis
RP: Recommended Practice
UTS: Ultimate Tensile Strength

2.2 Nomenclature and Definitions

Active fire protection: Equipment, systems and methods which, following initiation, may be used to control, mitigate or extinguish fires

Automatic depressurisation: Automatic depressurisation is initiated directly and automatically from the fire and gas (F&G) detection system. The signal routing may be via the emergency shut down (ESD) system. In some cases time delays are introduced in order to allow isolation valves to close prior to start of the depressurisation operation

Deluge system: System to apply firewater through an array of open spray nozzles by the operation of a valve on the inlet to the system

Depressurisation: Controlled reduction of pressure by disposal of fluids to a disposal system (normally the flare or vent system)

Depressurisation system: The system designed to enable depressurisation, normally this consists of piping connected to the process segment, depressurisation valve (BVD) with associated

	actuators, instruments, etc, and orifices, tail pipes, flare/vent headers, knock out drum and flare stack and tip
Global average heat load:	The global average heat load exposes the entire process segment or a significant part of the segment. The load intensity is found by averaging over a given time period and area (ref. Appendix A). The global average heat load provides the major part of the heat input to the process segment and, hence, affects the pressure in the segment. Note that the heat input to the process segment is dependent on the heat load as well as the area exposed to that heat load. The global average heat load shall be used for the exposed area when calculating the heat input to the process segment
Fire and explosion strategy:	Results of a process that uses information from the fire and explosion evaluation to determine the measures required to manage these hazardous events and the role of these measures
Fuel controlled fire:	A fire scenario where the supply rate of fuel is the limiting factor for the fire size and development
Incident radiation heat flux:	The gross radiation heat flux exposing an object. Normally, only a fraction of the incident radiation flux will be absorbed by the object
Incident heat flux:	The gross radiation heat flux + the convective heat flux to an object at ambient temperature
Jet fire:	Ignited release of pressurised, flammable fluids
Local peak heat load:	The local peak heat load exposes a small (local) area of the process segment to the peak heat flux. The load intensity is found by averaging over a given time period (ref. Appendix A). The local peak heat load, with the highest heat flux, determines the rupture temperature of different equipment and piping within the process segment. The local peak heat load has a marginal influence on the pressure profile within the process segment
Longitudinal weld factor:	Factor which compensates for lower degree of NDT of the longitudinal weld for welded pipes; factor less or equal to 1.0. Describes the allowable utilisation of the nominal wall thickness
Manual depressurisation:	Manual depressurisation implies that operator action is required in order to initiate the depressurisation process. If depressurisation is initiated automatically by a high level ESD and that level of ESD requires operator action, this is still considered manual depressurisation. Manual depressurisation can be initiated either by a master push button on a matrix, by individual push buttons on a matrix or via the computer consoles

Mill tolerance:	The allowable production tolerances for pipe wall thickness, widely used value; +/- 12.5 %
Passive fire protection:	Coating or cladding arrangement which, in the event of fire, will provide thermal protection to restrict the rate at which heat is transmitted to the exposed object
Pool fire:	Combustion of flammable or combustible fluids spilled and retained on a surface
Process segment:	All equipment and piping within one depressurisation volume. The ESD or PSD valves connected to the segment define the battery limit of the depressurisation volume. The process segment is depressurised through the BDV and the depressurisation orifice. A single pressurised vessel, storage or transportation tank etc. can also be defined as a process segment.
Stoichiometric combustion:	A combustion process where the supplied fuel is completely burnt in air with no excess air.
Tail pipe:	The pipe between the depressurisation orifice or the PSV and the flare header or sub header.
Ventilation controlled fire:	A fire scenario where the supplied air is the limiting factor for the fire size and development.

3. GENERAL PRINCIPLES

The protection of process systems exposed to fire is achieved by a number of measures which, when brought together, constitute the total fire protection scheme for the systems.

The main objective in this context is to prevent a small (and controllable) fire to escalate to a larger (and uncontrollable) fire that may threaten personnel outside the vicinity of the initial fire and even endanger the whole platform or plant.

Hence, a key issue is hence to prevent escalation to nearby process equipment resulting in loss of containment and release of significant quantities of combustibles.

Full utilisation of the flare system capacity by fast depressurisation should be aimed for in order to prevent unacceptable escalation and to minimise the use of PFP.

Escalation in terms of structural damage and collapse or critical damage to fire partitions is not addressed as a part of this guideline.

The key parameters relevant for the fire protection of process equipment are:

- Depressurisation
- Passive fire protection
- Deluge/water spray systems
- Pressure safety valves
- Selection of process equipment/materials
- Limitations of process inventories
- Fire scenarios
    - * Layout
    - * Ventilation
    - * Drainage
    - * Nature of combustible fluids
    - * Nature of release (time dependent leaks/duration).

These parameters are further elaborated in Chapter 4 of this guideline.

The main principles for achieving an optimum fire protection of the process system are:

- Maximum utilisation of the flare system
- Selection of material quality
- Selection of material thickness/pressure classes
- Sizing of process segments/location of sectionalising valves (inventory/volume)
- If necessary, application of passive fire protection
- Active fire protection systems.

It should be noted that a similar type of evaluation should be performed also for the flare system itself to ensure the integrity of the flare system during a fire and depressurisation scenario.

Figure 3.1 shows the main principles of the iterative procedure for analysing and dimensioning the process system exposed to fires with the objective of minimising the use of passive fire protection.

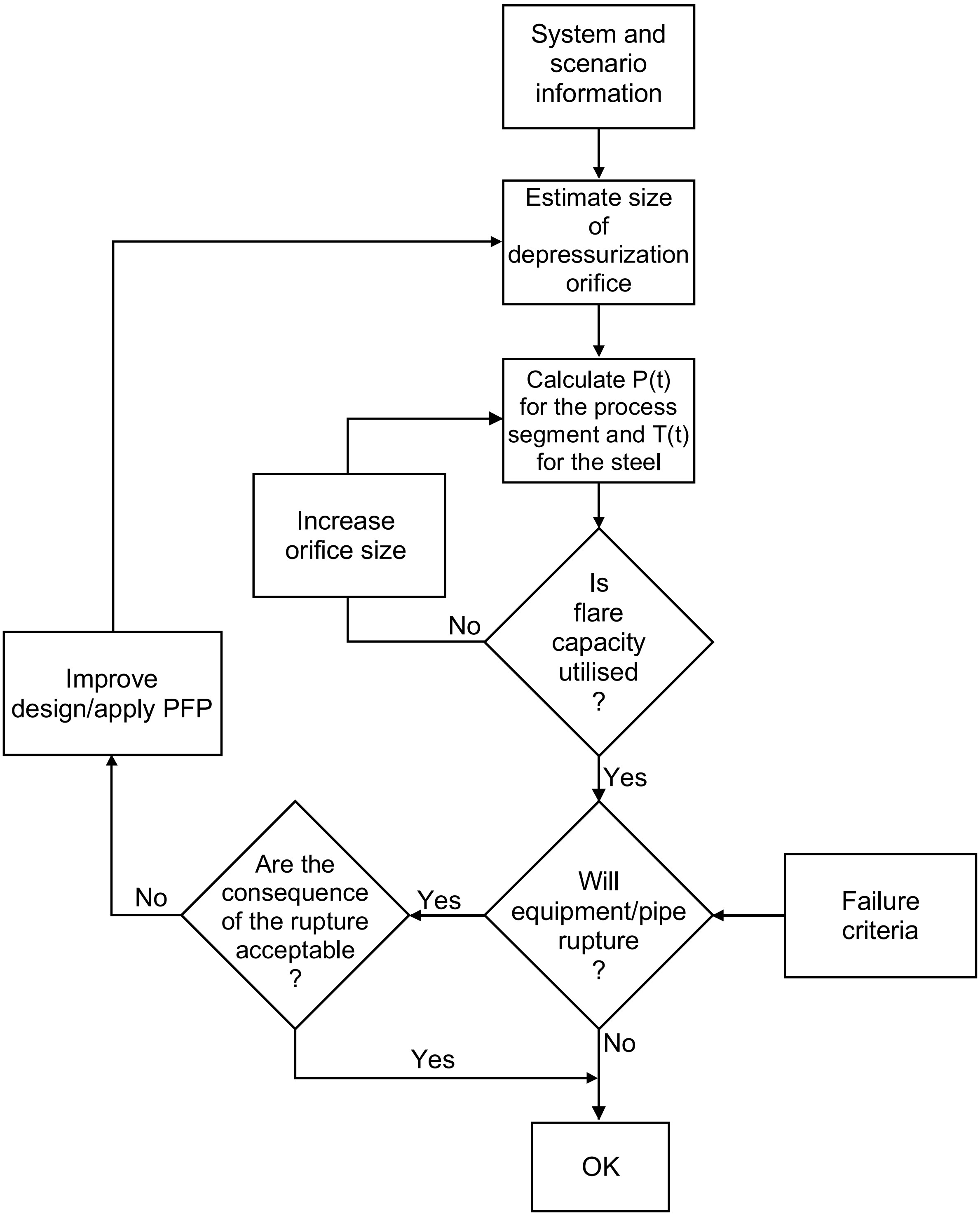

Figure 3.1: Simplified Procedure for Optimising Design of the Depressurising and Passive Fire Protection Systems for Process Equipment

The main principles of the iterative calculation procedure are described below. A more detailed and comprehensive description of the procedure is given in Chapter 5 of this guideline.

System and Scenario Information

It is vital that the input data for the analysis is as correct and complete as possible. The available information will to some extent depend on the status of the project. In an early phase of a project the input data is often not decided and in these cases a best guess based on similar projects or common practice should be used.

The input for a complete analysis includes:

- Description of the process segment to be analysed
    - Process segment layout including equipment, pipes, valves, etc.
    - Geometry of process segment (volume, area, weight, etc.)
    - Process parameters (operating pressure, temperature, composition of fluids, etc.)
    - Material data (type of construction material for pipes and equipment, dimensions, properties at elevated temperatures, etc.)

- Description of the depressurisation system characteristics
    - Method for depressurisation initiation (manual or automatic)
    - Time delay for initiation of depressurisation
    - Capacity of the flare system (capacity of the flare system may be influenced by the analysis i.e. in some cases it will be an output from the procedure)

- Description of the fire scenarios
    - Type of fire
    - Fire duration
    - Fire size (exposed area)
    - Heat loads (global and local).

Size of Depressurisation Orifice

Estimate the size of the depressurisation orifice for an uninsulated process segment exposed to a global average heat load. As a starting point the orifice size corresponding to a pressure reduction down to 7 bar within 8 minutes could be used. Note that this procedure is iterative and the orifice size is one of the key parameters to vary.

Calculate P(t) and T(t)

The pressure (P) in the system as function of time (t) shall be calculated with due consideration to the effect of the heat input and the effect of the depressurisation system. In this context the global average heat load should normally be used. A rigorous thermodynamic model will be required to perform these calculations.

The steel temperature (T) as function of time (t) shall be calculated for all geometries of the process equipment and piping exposed to fire. For these calculations the local peak heat load shall be used.

Is the Flare Capacity Utilised?

The total depressurisation rate for the plant needs to be checked against the capacity of the flare system. If the flare system capacity is overloaded the depressurisation rates must be reduced (or the flare capacity increased). Reduction of the depressurisation rates might imply need for passive fire protection.

On the other hand if the flare system capacity is not fully utilised the depressurisation rates should be increased (even if the failure criteria is met), this to enhance the overall inherent safety of the plant design.

Failure Criterion

A failure criterion for the material applied in the process segment need to be established. Normally such a criterion requires knowledge of the ultimate tensile strength (UTS) of the material at elevated temperatures. Other more sophisticated failure criteria might also be applied, e.g. using elongation/deformation as failure criteria, see Appendix C.

Will Equipment/Piping Rupture?

Based on the P(t), T(t), and the failure criterion it can be decided whether parts of the process equipment or piping will rupture or not. Note that T(t) will vary for the different elements of the process segment.

Criteria for Unacceptable Consequences of Rupture

Even if it is a key issue to avoid any rupture, some criteria for deciding if the consequences of a rupture are unacceptable should be established. The main objective is to prevent a small fire to escalate to a large fire.

If parts of the process equipment do rupture, then it needs to be considered whether this implies unacceptable consequences or not. Normally this relates to the released quantities of flammable fluids, the composition of the released fluid (gas/liquid) and the pressure in the system at the time of the rupture. Pressure vessels that rupture tends to form missiles more easily than pipes. This implies that the maximum acceptable rupture pressure varies for pipes and vessels. Other consequences such as pressure pulse and impact on neighbouring piping should also be considered.

All ruptures that may lead to an escalation to neighbouring fire areas are unacceptable. Also blockage of main escape ways or exposure of essential areas, rooms or systems of the installation should be considered. In this case probability and duration of the exposure should be taken into account.

As a simple rule, exceeding any of the following criteria is normally considered to make a rupture unacceptable:

- Given amount of total released hydrocarbons
- Given amount of released gas including flash fraction of condensate/LPG
- Given vessel pressure
- Given pipe pressure

For quantification of these criteria, see Chapter 4.7

Other criteria may be derived based on a detailed consequence analysis of rupture in the process segment in question. Aspects that could justify higher pressures or quantities could be location of the segment in relation to other systems or functions that may be at risk, unmanned facilities, etc.

Improve Design

Improvement of the design might involve a number of the factors already mentioned in this outline procedure. In addition a number of other factors may be considered.

Improvement of the design might, hence, involve:

- Increase the flare system capacity/improve utilisation of the flare system
- Change the material in the system
- Provide passive fire protection (note: If PFP is applied on a segment, this will allow for a longer depressurisation time and hence increase the duration for a potential jet fire from this segment)
- Change (increase) the wall thickness of the system components.

See Chapter 5 of this guideline for a more detailed description of the procedure.

4. FIRE PROTECTION OF PRESSURISED EQUIPMENT AND PIPING

4.1 Depressurisation

Depressurisation systems are installed in order to

- reduce the pressure in a process segment in the case of a fire exposing the segment in question. A reduction in pressure implies reduced material stress and, hence, reduced risk of rupture due to heating caused by the fire
- reduce the leak rate and leak duration from a leaking process segment (and, hence, also reduce the associated fire in case the leak is ignited)
- remove combustibles (gas/liquid) from the fire area by disposal to the flare system
- reduce the pressure and inventory of the process segment to an acceptable level prior to rupture if rupture can not be avoided
- depressurise the system in case of normal maintenance
- in some cases avoid leakage at process upsets, e.g. in case of loss of compressor seal oil/seal gas

Depressurisation systems shall be provided for all process segments containing more than 1,000 kg of hydrocarbons. If the content of the system is gas or liquid that will vaporise at rupture (such as LPG), a system for depressurisation shall be provided even for smaller process segments, Ref. /3/.

Traditionally depressurisation systems have been designed in accordance with API RP 520 and API RP 521 which normally imply that the depressurisation system should be capable of reducing the pressure to 7 barg or 50 % of the design pressure of the system (whichever is lower) within 15 min. However, research and large scale testing (e.g. the project 'Blast and Fire Engineering for Topsides Structures') indicates that this does not necessarily prevent catastrophic type rupture of fire exposed systems due to expected higher local heat loads than recommended by API RP 521. A faster depressurisation or use of passive fire protection is therefore normally required in order to avoid critical escalation of a fire.

A key factor, which also determines the effectiveness of the depressurisation system, is the method for initiation, i.e. the time span from the onset of the fire until the activation of the depressurisation system. Initiation of depressurisation could be either manual or automatic. Generally automatic depressurisation is recommended. This will lead to shorter depressurisation time and therefore reduce the need for PFP.

In case of manual initiation of depressurisation, the duration from the onset of a fire until the depressurisation is activated depends on a number of factors:

- Complexity of the plant
- Manning level (in the control room and process area)
- Fire detection systems
- Procedures, training, etc.
- Other work tasks assigned to the personnel during an emergency.

It is commonly recognised that manual initiation prior to 3 minutes after the onset of the fire should not be accounted for, Ref. /3/.

Automatic initiation of the depressurisation system implies that the system is activated automatically by the F&G detection system. Provided that the plant is adequately covered by a suitable detection system, instant (for all practical purposes) initiation of the system may be accounted for. (Note that automatic initiation of the depressurisation system by a high level ESD does not necessarily imply automatic initiation in this context, this depends on the F&G/ESD logic configuration).

Generally the estimated time from the onset of a fire until the initiation of the depressurisation should be justified.

Depressurisation may be performed:

- For a process segment
- For a fire area
- For the entire plant.

In case of manual initiation of depressurisation, due consideration should be paid to the complexity of the activation procedure, risk of maloperation as well as time to initiate the depressurisation.

In general it is strongly recommended to provide a system that is based on simultaneous and automatically initiated depressurisation of the entire fire area or plant.

If a system is based on sequential depressurisation of different fire areas, focus should be put on avoiding pipe segments protruding into a fire area that is not included in the depressurising sequence of the area. Alternatively such segments should be provided with passive fire protection and the neighbouring fire area depressurised after a time delay.

Sequential depressurisation is often applied in order to avoid overload of the flare. Sequential depressurisation may be justified based on detailed calculations of the fire resistance of the system or based on segregation (based on distance or by fire partitions).

Depressurisation of the plant may be a dimensioning scenario for the flare system. However, in many situations other load cases are found to be dimensioning, e.g. process upsets, blocked outlets, etc.

The general principle when designing the depressurisation system should be to utilise the maximum capacity of the flare system, i.e. keep the depressurisation time as short as possible within the design limits of the flare system.

Design of the depressurisation system is a complex issue involving not only rigorous thermodynamic and process calculations, but also complex fire modelling and heat transfer phenomena.

4.2 Fire Relief

All pressure vessels should be provided with a pressure relief valve, PSV, for fire protection according to ASME Ref. /4/. Heat exchangers are normally also provided with PSVs for thermal relief, but this should be justified based on the possibility for thermal input from a process point of view.

In many situations PSV's are provided for process relief purposes, i.e. to provide overpressure protection in case of process upsets.

Normally, if a PSV is required to handle process upsets this becomes the dimensioning load case for sizing the PSV.

Pressure safety valves (PSV's) which are designed for fire relief are normally small since they shall

- relieve gas which is vaporising from the liquid during a fire and/or
- relieve gas which is expanding due to heat input or
- relieve the expanding liquid for a 100 % liquid filled system.

All these relief rates are normally small compared to other relief scenarios. Usually the more volatile the liquid is, the larger the fire relief valve will be.

PSVs which are sized for fire relief shall be sized for a situation where the depressurisation valve (BDV) does not open, i.e. the same input parameters and the same physical principles as for the depressurisation calculations apply (system volume, area, weight, fluid properties, fire input etc).

The fire relief rate from a 100 % liquid section shall be the maximum volume expansion per time, dV/dt.

It is important to note that a PSV will not reduce the pressure in the process segment, but only limit the pressure to increase above the set point of the PSV + the maximum accumulated pressure. The maximum allowable accumulated pressure for multiple fire relief devices designed in accordance with API might be as high as 121 % of the design pressure.

As a result, a PSV will not prevent a vessel or piping from rupturing if the material in the system is heated above the critical temperature (which will be low, typically less than 500-600 degree Celsius due to the high pressure in the system).

The rupture of a pressure vessel or pipe may occur even before the PSV opens and starts relieving the inventory. This is often related to situations where the heat input into the fluid is low whereas the heat input to the wall is high. Such situations occur when

- there is a local fire only
- a segment is partly fire insulated resulting in heating of a small part of the segment (the more insulation the less is the probability for the PSV to open)
- heating of the non-wetted material only (the inner side of the material is a gas filled volume).

Insulating the liquid area (and hence reducing the boil-off) will reduce the required size of a fire relief valve on a segment containing a liquid. This effect is more relevant for light liquids (condensate, LPG, LNG).

4.3 Passive Fire Protection, PFP

In general the use of PFP should be avoided if possible, i.e. the prime focus should be to design a depressurisation system with the capacity to reduce the pressure in the system fast enough to avoid critical escalation of the fire.

The main concerns relating to use of PFP are:

- Increased corrosion of materials covered by PFP
- Reduced possibilities for inspection and maintenance of equipment covered with PFP
- Increased weight
- Increased need for space
- Increased need for maintenance of the PFP
- Increased cost.

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.

The main principle for applying PFP is to "buy time". This will allow the depressurisation system to reduce the pressure down below the critical level or until the critical heat load from the fire is over (either to avoid rupture or to ensure that the consequences of a rupture are less severe). The objective is to prevent a small fire to escalate into a large fire.

If parts of a process segment are insulated due to other purposes (heat conservation, frost protection, noise, etc.) the selected type of insulation should be considered to be of PFP type.

For a process segment various parts of the system could be insulated depending on the purpose of the insulation:

- Wetted surfaces, i.e. parts of the system that has a liquid inventory. PFP will reduce the evaporation or boil-off and, hence reduce the pressure build up within the system

- Dry surfaces, i.e. parts of the system that has a gas inventory. PFP will mainly reduce the material temperature (although it would also reduce the pressure build-up due to thermal expansion of the gas)

- Vessels and piping will behave differently in a fire situation due to different surface area to volume ratio. The rupture mechanics and hence 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. Other liquid filled pipes may as well become dry by forming gas pockets in given parts, thus forming a weak point for overheating by fire, also see Chapter 5.8

- Valves, actuators and power supply to actuators (if relevant) of prime importance in this context are the isolation valves which constitute the boundary of the process segment and the depressurisation valve (BDV)

- Flanges and valves located in pipes that need to be fire insulated shall normally be insulated. Flanges/valves located in piping, which is not insulated, should be evaluated for the need to insulate as they may rupture prior to the pipes. Flanges and valves in a pipeline communicating with liquid or gas reservoirs containing hydrocarbon content above the acceptance criteria (Ref. Chapter 4.7) at the time of rupture should generally be insulated

- Pipe supports, in order to ensure the integrity of the pipe
- Vessel supports, in order to ensure the integrity of the vessel
- Secondary structural members as required for pipe and vessel supports

When selecting PFP system and material due consideration should be paid to materials and systems that will not accumulate humidity/water and, thus, promote corrosion. Condensation due to varying environmental conditions as well as varying process temperatures should be born in mind in this context.

Pipe and equipment materials as well as coating systems should be selected with care to minimise potential corrosion problems on systems covered with PFP.

Possibilities for removal and replacement in connection with inspection and repair should also be focused upon.

In general a life cycle optimisation should be aimed for when selecting PFP.

4.4 Integrity of Flare System

The integrity of the flare system during a fire situation is of prime importance. This is also focused in PSA regulations, Ref. /5/, as well as in NORSOK, Ref. /3/. Rupture of parts of the flare system during a fire might result in a massive release of hydrocarbons (e.g. due to an ongoing depressurisation) and cause a severe escalation of the accident.

Integrity of the flare system including support arrangements should be analysed in a similar way as described for process systems in general. The key issue is to document the integrity based on the time/temperature profile of the materials exposed to fire versus the time/pressure profile of the system caused by the depressurisation operation.

Two critical aspects are pinpointed in this context:

- **Time to start of the depressurisation.** The flare system pressure will most likely be close to atmospheric in the time period up to initiation of the depressurisation. The highest-pressure peak is normally experienced just after initiation of the depressurisation. If a part of the flare pipe has been exposed to fire for a few minutes it might not have sufficient residual strength to sustain the initial pressure load. Manual or automatic initiation of the depressurisation will play an important role in this context, Ref. Chapter 4.1

- **Cool down due to flowing gas.** During a depressurisation the flare pipe will be cooled by the flowing gas, which will be relatively cold due to the Joule-Thomson effect resulting from gas expansion. This effect can be accounted for in the thermal calculations. However, this cooling effect will obviously not come into force until depressurisation is initiated. This again underlines that the most critical moment for the flare will be just after initiation of the depressurisation process. In particular this is important for delayed depressurisation.

It should further be noted that the cooling effect would only be present in the sections of the flare system that will experience a flow during a depressurisation. This flow may also vary significantly from one process segment to another in terms of flow rate and duration. Pipes in the flare system which are only connected to PSVs or PVs will not experience any flow during a depressurisation operation and will not benefit from this cooling effect.

Generally it must be expected that the flare system must be provided with passive fire protection in order to ensure the integrity of the system. Exceptions from this are plants with small gas inventories and/or plants with automatic initiation of depressurisation. However, in the latter case pipe sections downstream PSVs and PVs will most probably need to be protected.

4.5 Deluge/Water Spray

Deluge or water spray systems are installed to

- provide cooling of fire exposed equipment and structures
- reduce the temperature of the fire and hence the heat load and consequently the temperature build up in exposed equipment
- provide a means to apply foam to extinguish hydrocarbon pool fires.

In principle four types of deluge protection are provided:

- Equipment protection designed to provide dedicated coverage of critical equipment such as pressure vessels and wellheads
- Area protection designed to provide non-specific coverage of pipe work and equipment within hydrocarbon handling areas
- Structural protection designed to provide dedicated coverage of critical structural members
- Water curtains to reduce thermal radiation and to control the movement of smoke.

Even though it can easily be argued that a comprehensive deluge/water spray system will have a positive effect in case of a fire it has not been commonly accepted by NPD to give credit for this when designing PFP systems.

The reliability of the deluge/water system is of importance in this context. Reliability in this sense includes the reliability of water supply as well as the delivery of water on the actual location; this latter topic could e.g. be influenced by the risk of clogged nozzles.

It should be further noted that the direct cooling effect by dedicated deluge on equipment surfaces in case of jet fires is questionable, even though the jet flame itself will be cooled by entrained water droplets from the deluge systems.

4.6 Fire Scenarios/Heat Fluxes

In order to enable calculation of the heat input to the equipment in question the actual fire scenarios and heat fluxes must be established.

The fire scenarios need to be determined and described as:

- Type of fire
- Fire duration
- Fire size (exposed area)
- Heat fluxes (global and local).

The fire scenarios that shall be accounted for can often be found in the Quantitative Risk Analysis (QRA), the Design Accidental Load (DAL) specification, or Fire and Explosion (FES) strategy for the actual process system or area to be analysed. In the QRA, DAL specification, or FES strategy the possible types of fire, leak positions and estimated duration are evaluated. The loads and duration given in these documents are often very rough estimates and much can then be achieved by taking actual process parameters into account and perform more accurate calculations as indicated in Appendix A.

It should be noted that this guideline focuses on preventing a small fire from escalating into a large fire, ref. Chapter 3. While the DAL specification often focuses on large fires, this will not necessarily be applicable in this context. The typical fire that should be focused is a small to medium size fire.

Usually hydrocarbon fires are differentiated in two types of fire or combination of these:

- Pool fires (liquid)
- Jet fires (gas or liquid).

The fire properties will heavily depend on degree of confinement as well as air supply (fuel/ventilation controlled). In this guideline focus is primarily on fuel controlled fires (small fires that should not escalate to large fires). However, for facilities with limited ventilation, e.g. mechanical ventilation, even small fires might become ventilation controlled. This may influence the heat loads, in particular the global average heat loads.

It is important to note that high-pressure (typical above 3-6 bar reservoir pressure) leaks of hydrocarbon liquids (oil/condensate) in many situations will burn as a liquid jet with much the same characteristics as a gas jet fire, and as a consequence should be treated as a gas jet fire. Generally, liquid jet fires > 2 kg/s which are fed from a reservoir > 4,000 kg is not considered in this guideline since this is already defined as a large fire.

Based on process data (volume, mass, pressure, temperature, fluid composition, initial leak rate, etc.) the duration for different leak rates should be estimated. For pool fires due consideration should be paid to the surface where the spill is accumulated and the drainage facilities in the area. Note that a pool fire may last substantially longer than the leak itself if liquids are allowed to accumulate. A liquid spill may also cause a run down of oil onto equipment causing a so called running liquid fire with a much higher burning rate per projected deck area than a liquid pool fire.

Typical incident heat fluxes for fuel controlled pool fires and jet fires can be found in Table 4.1. These are based on observed heat fluxes obtained from a number of experiments as well as a number of CFD calculations.

The transient variation of the fire shall also be reflected, especially for jet fires. The transient behaviour due to decreasing leak rates will both influence the size of the exposed area and also the total heat flux to the process segment.

Small to medium sized fires are generally fuel controlled but in enclosures with limited air supply and in highly congested areas the fires may become ventilation controlled even for small supply rates of fuel. Such fires may result in higher global average heat fluxes than given in Table 4.1.

Table 4.1: Proposed Incident Heat Fluxes for Fuel controlled Fires fPr protection of pressurised Systems. No Credit for Water Deluge is given

	Jet fire		Pool fire
	For leak rates m > 2 kg/s	For leak rates m > 0.1 kg/s *)	
Local peak heat load	350 kW/m^2	250 kW/m^2	150 kW/m^2
Global average heat load	100 kW/m^2	0 kW/m^2	100 kW/m^2

*) This calculation is for an object located close to the leak source. The heat flux will vary during the fire duration, and 250 kW/m^2 is used as the average incident heat flux

Jet Fires

The global average heat load is used for calculating the pressure profile, P(t) and is time and area averaged over the fire exposed part of the segment. If the process segment is very large (compared to the fire) a lower global average heat load might be justified.

For a jet fire in an area containing several process segments the dimensioning segment, i.e. the segment giving the longest leak duration, given a critical leak rate m_{crit} (kg/s), must be identified.

For jet fires **two different scenarios** shall be analysed **separately**:

1. 350 kW/m^2 for a duration t' which corresponds to a leak rate $m > m_{crit}$, m_{crit} = 2 kg/s
2. 250 kW/m^2 for a duration t'' which corresponds to a leak rate $m > m_{crit}$, m_{crit} = 0.1 kg/s

where

t' is the time from start of the fire until the leak rate is reduced below m= 2 kg/s
t'' is the time from start of the fire until the leak rate is reduced below m= 0.1 kg/s

The above shall be interpreted as:

For jet fire scenarios:
Case 1) 350 kW/m^2 local heat load used in calculation of local steel temperature.
100 kW/m^2 global heat load shall be used for system pressure calculations. The duration for this scenario is t' seconds.

Case 2) 250 kW/m^2 local heat load used in calculation of local steel temperature.
0 kW/m^2 global heat load shall be used for system pressure calculations. The duration for this scenario is t'' seconds.

These two scenarios shall not be combined i.e. the local heat load of 350 kW/m^2 for a given time period t' shall not be followed by a local heat load of 250 kW/m^2 in the time interval t''-t', but be analysed separately.

The reason that case 1 and 2 shall not be combined is that the flame from a specific leak will expose different locations during the initial phase (> 2 kg/s) and the late phase (< 2 kg/s). Hence, a specific location will be exposed to only one of the heat loads from a specific leak.

The difference in global heat load between jet fires with leak rates less than 2 kg/s and jet fires with leak rates larger than 2 kg/s is due to the observation that smaller jet fires will have a limited flame volume compared to the typical size or extension of the process segment to be evaluated. This small flame volume results in a limited heat effect outside the flame region.

When calculating the jet fire duration, the worst case initial leak rate (i.e. the initial leak resulting in longest duration of $m > m_{crit}$) should be used for each of the two scenarios. Credit should in this context be given to the effect of the depressurisation system. See Appendix A for calculation of worst-case initial leak rate.

Pool Fire

For pool fire scenarios:

- 150 kW/m^2 local heat load shall be used for the calculation of local steel temperature
- 100 kW/m^2 global heat load shall be used for system pressure calculations.

The duration for which a pool fire is evaluated should be equivalent to the time for which structural fire protection in the area is designed; normally this is defined in the DAL specification.

Fire calculations

An alternative approach to assess the heat fluxes and the size of the fire (exposed area), is to calculate realistic fire scenarios for the plant in question, e.g. by CFD modelling. If this approach is chosen, the methods and computer tools used should be validated. A justification for the chosen scenarios and an evaluation of the scenarios not handled should also be given.

4.7 Unacceptable Consequences of Ruptures

In the event that a pressure vessel or a pipe ruptures due to fire exposure the acceptability of this depends on the consequences of such a rupture.

In accordance with the ALARP principle (keep the risk **A**s **L**ow **A**s **R**easonable **P**racticable) the aim is to prevent **any** rupture. However, a criterion for unacceptable rupture needs to be established.

In principle the governing criteria is that a rupture should not result in a severe escalation of the initial fire (i.e. prevent that a small fire becoming a large fire).

All ruptures that may lead to escalation to neighbouring fire areas are considered unacceptable. Also blockage of main escape ways or exposure of essential areas, rooms or systems of the installation should be considered. In this case probability and duration of the exposure should be taken into account.

The consequences of a rupture are mainly dependent on:

- Hydrocarbon quantity that will be released as a result of the rupture
- How fast the hydrocarbons are released
- Whether the released hydrocarbons are in gas or liquid form
- Pressure in the system at the time of the rupture
  - Risk of missiles
  - Risk of damage to neighbouring piping when a pipe bursts due to possible large deflections
- Location of the rupture compared to systems/equipment/functions at risk
- Risk of endangering personnel outside the immediate vicinity of the area of the initial fire.

As simplified rules based on the general acceptance criteria, exceedance of either of the following criteria is considered to make a rupture unacceptable:

- Released quantity of hydrocarbons (the sum of gas and liquid) > 4 tons
- Released quantity of the sum of gas, initially flashed fraction of condensate or LPG > 1 ton
- Pressure at time of rupture of pressure vessels > 4.5 barg
- Pressure at time of rupture of piping > 20 barg
- Rupture prior to 3 minutes after the onset of the fire.

Process segments containing less than 100 kg gas, initially flashed fraction of condensate or LPG at the time of rupture are allowed to rupture irrespective of the pressure in the system.

The reason for distinguishing between vessels and pipes with regard to maximum acceptable pressure at time of the rupture is the higher risk of missile effects for vessels.

The time criterion is based on time to evacuate the area in the vicinity of the fire.

For flare systems rupture should not occur at all. The background for this requirement for the flare system is that the consequences of a rupture might be severe. During depressurisation the system pressure is reduced, also for the segment feeding the fire. The heat load from the initial fire will therefore be reduced and, hence less critical for the integrity of the flare system. The integrity requirement might imply the need for improved support of the flare piping and header systems.

For small bore gas piping the pressure and quantity criteria can be deviated if it is documented that the resulting release rate will not result in a critical escalation of the accident. However, ruptures causing gas release rates > 2 kg/s are considered unacceptable.

4.8 Selection of Process Equipment

The type of process equipment, choice of materials, selection of dimensions and pipe class, etc. will influence the total performance of the process segment exposed to fire.

The flexibility in these choices should be used to accomplish the overall objective of minimising the need for passive fire protection.

In principle this implies that an inherently safer design should be aimed for whenever possible.

Examples of this might be:

- Increasing the pipe wall thickness above what is normally required from a process point of view might in some cases prove to be cost effective if this implies that PFP is not required
- Selection of materials with better performance at elevated temperatures could reduce or eliminate the need for PFP. This could prove to be cost effective if the material fulfils the other "conventional" requirements required from a process point of view
- Selection of inherently more fire resistant flange/bolts types could reduce the need for PFP
- Selection of fire resistant valves might reduce the need for fire insulation.

4.9 Importance of Reliable Material Data

Figure 4.1 illustrates the characteristic behaviour of process components (pipes/ vessels) in terms of applied stress (von Mises stress) compared to the allowed stress (tensile strength) during fire loading and depressurisation.

The thick red curve is the actual ultimate tensile strength as function of temperature and indirectly of time for the material data given in Appendix B. The dashed blue lines reflect the uncertainties in this data. The lines marked (a), (b) and (c) can be regarded as the actual von Mises stress for three different pressure profiles for a specific pipe component in the process segment.

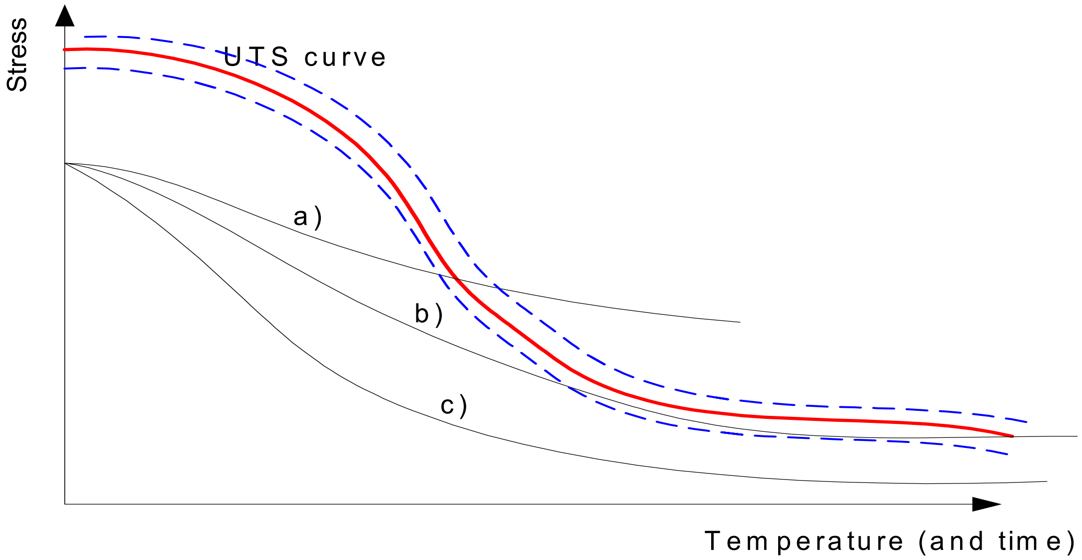

Figure 4.1: UTS (Ultimate Tensile Strength) and von Mises Stress Curves

For a component or process segment behaving as a type (a) system, the uncertainties in the UTS value has little effect on the conclusion regarding time to rupture.

System (b) is a system where the influence of the uncertainty of the UTS is significant with respect to the conclusion of time to rupture.

System (c) is a system where the influence of the uncertainty of the UTS with respect to the conclusion of time to rupture, is smaller than for system (b).

Before performing the complete analysis according to the procedure given in Chapter 5, it is recommended to do some initial calculations trying to establish whether the starting point of the analysis is a system (a), (b) or (c). This information can be useful with respect to the choices made during the analysis.

5. PROCEDURE FOR OPTIMISING FIRE RESISTANCE

5.1 Introduction to the Calculation Procedure

The recommended calculation procedure for optimising the fire resistance for a process system is illustrated in Figure 5.1. The procedure outlined starts out with a given flare system capacity. If there is a significant demand for PFP, it should be considered to increase the flare system capacity to decrease the use of PFP by repeating the optimising procedure.

Note that a key objective is to minimise the use of PFP and ensure optimum utilisation of the depressurisation and flare systems.

Each of the main steps of the procedure is described in the following with recommended input values for the main characteristics influencing the calculations. The background for the recommendations as well as alternative approaches is outlined in the appendices to this guideline.

5.2 Information prior to the Calculations

Prior to start of the calculation procedure key characteristics relating to the process segment, the depressurisation system, and the potential fire scenarios must be clarified. Depending on the maturity of the project some of this information may have to be estimated.

Process Segment

- Process segment layout
- Location of isolation valves defining the limits of the segment
- Volume of the segment
- Pressure of the segment
- Temperature of the segment
- Fluid composition of the segment
- Wet and dry areas of the segment
- Material types
- Dimensions of components, incl. material thickness.

Depressurisation System

In principle the depressurisation rate is the key parameter to vary in the calculation procedure. However, some information regarding this system is also important to clarify prior to start of the calculations:

- Method for initiation of depressurisation (manual or automatic)
- Time delay for initiation of depressurisation
- Total capacity of the flare system.

For manual initiation the time to initiate depressurisation should be justified. A time to initiate depressurisation < 3 minutes should generally not be accounted for in the analysis.

For automatic initiation the time could be set at instantaneous + the time it takes to close the segment's inlet sectionalisation valve. However, an adequate fire detection system including F&G and ESD logic should justify this. Generally automatic initiation of depressurisation is recommended.

Fire Scenarios

The fire scenarios determine the heat input into the system and must be clarified prior to starting of the calculations.

- Define whether the process segment will be exposed to a local fire with or without global fire. Due consideration should in this context be paid to the size and extension of the process segment compared to the size of the fire

- Define the initial heat flux of the local fire with or without global fire

- Define the duration and size of the fires. Note that whenever the size of a depressurisation orifice is changed, this will, to some extent, influence the duration of the dimensional fire from this particular depressurisation segment.

For further details see Chapter 4.6 and Appendix A.

Material Data

Material data will be required to determine if/when a rupture will occur.

- Obtain material data at elevated temperatures (up to 800-1,000 C) for the materials in the process segment. The recommended simplified burst analysis described below requires UTS data. Note that several material qualities may be applied within the same process segment.

Experience shows that it takes considerable time to obtain such data from the pipe and equipment vendors. It is therefore recommended to specify that the pipe and equipment vendor should supply such data as input to the material datasheet. It should be established whether the obtained data are "guaranteed minimum values" or "typical values". "Guaranteed minimum values" will typically be in the range of 10-15 % lower than "typical values" and should be reflected when adding margins.

Material data for some standard type materials are provided in Appendix B. These values are "typical values".

Failure Criterion

A failure criterion for the material applied in the process segment need to be established.

The proposed method to define the failure criterion is to relate this to the UTS by taking into account safety factors for the UTS (material safety factor) and safety factors related to pipe manufacturing (pipe safety factor).

The Allowable Tensile Strength, ATS, defines the failure criterion as described below:

$$ATS = UTS \text{ x } k_s \text{ x } k_y$$

k_s = General safety factor for a specific material with known material data, normally 0.85 is recommended if material data are "typical values". If material values are “guaranteed minimum values” 1.0 can be used

k_y = Additional factor used for materials with missing or uncertain material data. This factor reflects the uncertainty in the UTS-values due to uncertainty in the data at high temperatures for the material used in the pipes. Normally this factor is 1.0 if the UTS-data is well documented. For missing or uncertain UTS-data, see Appendix B.

Reference is made to Appendix C for wall thickness to be used and for further details and alternative methods.

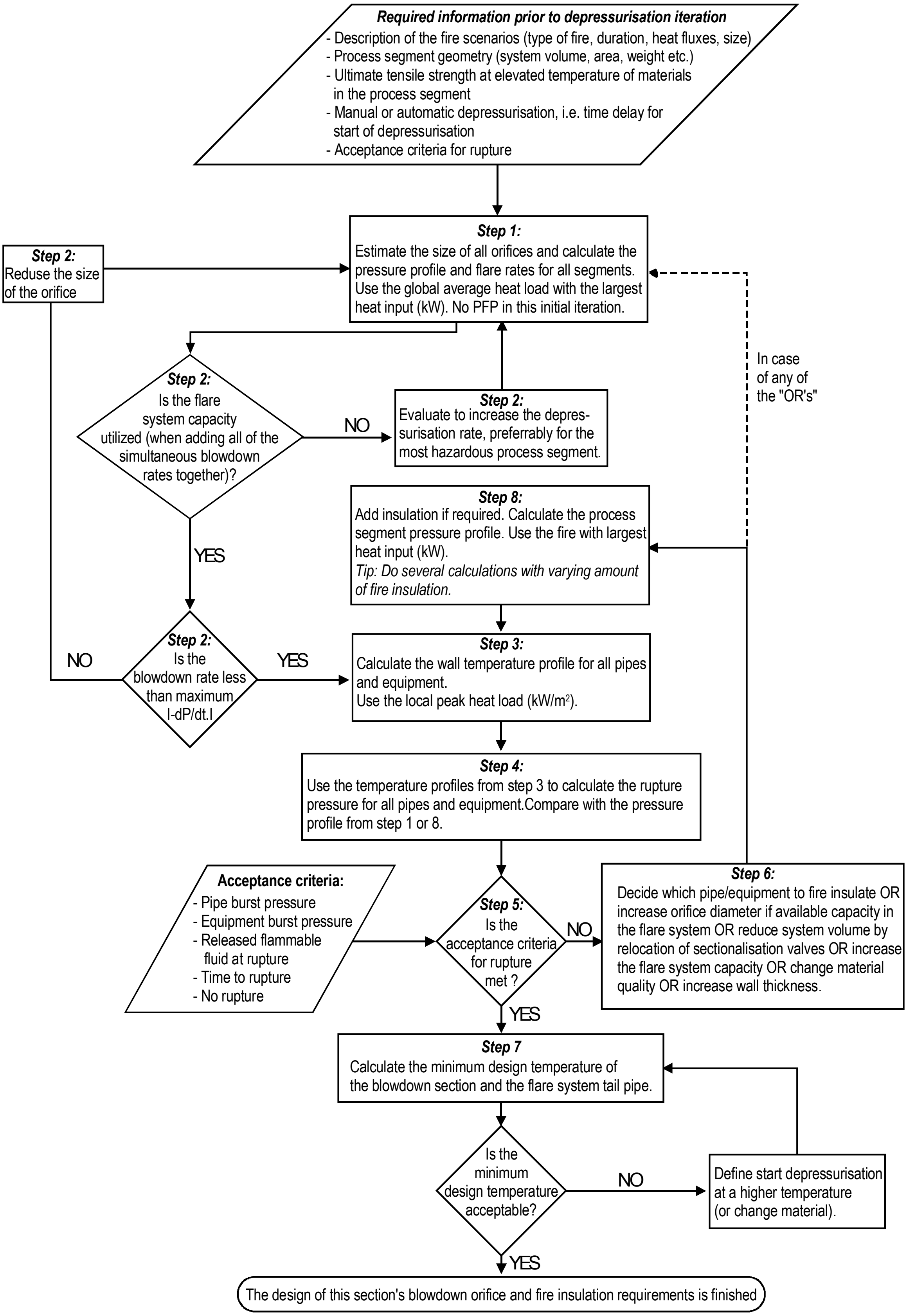

Figure 5.1: The Iteration Procedure for Depressurisation Design

5.3 Depressurisation Calculation (Step 1)

An initial estimate of the orifice must be established in order to enable the first depressurisation calculation.

A recommended initial estimate of the orifice size is a size that takes the pressure down to 7 barg in 8 minutes when exposing the process segment to a global average heat load. No PFP or AFP (Active Fire Protection) should be assumed in this first calculation. For global average heat loads, see Chapter 4.6 and Appendix A.

Alternatively, the initial depressurisation time could be based on typical heating times for the process elements exposed to the local peak heat load, i.e. the time to reach critical temperature for the components in question.

The calculation procedure should establish the pressure-time and temperature-time profile for the segment and should as a minimum include:

- Rigorous thermodynamics (multicomponent fluid and use of Equations of State)
- The heat transfer between the fire and the outer surface of the process segment should be split between convective and radiative fractions in order to reflect the heating of the exposed system
- The heat transfer between the process segment inner surface and the fluid inside the process segment should take into account the effects of convection, conduction and radiation as well as boiling of liquids. The fluid temperature for each phase shall be calculated individually. The heat transfer shall not be assumed constant throughout the calculation but shall be calculated for each time step
- The conductivity of the construction material shall be taken into account
- The mass transfer between the fluid phases (boiling, condensation)
- Fluid flow when relevant, i.e. flow regime calculation (laminar, turbulent). This is important input to the heat transfer and pressure drop calculations for pipes with internal flow, e.g. depressurisation lines
- Material properties, e.g. (tensile strength, heat capacity, conductivity - all temperature dependant)
- Fire modelling (emisivity, absorptivity, temperature, convection, initial flux, duration and size)
- Modelling of the depressurisation segment geometry (system volume, system outer and inner wall area, system weight, wall thickness, liquid and gas volume)
- Insulation (thickness and conductivity) - not to be used in the initial calculation
- Stress calculations (hoop and longitudinal).

The following conditions should be used for the calculations:

- Starting pressure should be equal to PAH (set point for the high pressure alarm of the component) or for compressors the settle out pressure
- Credit for insulation should only be given to PFP, i.e. equipment and pipes provided with insulation for other purposes should be regarded as uninsulated.

For each time step the following shall as a minimum be calculated:

- Pressure in the system
- Temperature in both fluid phases
- Fluid composition in each phase
- Flow rate through the orifice
- Liquid levels

- Temperature in the metal
- Temperature downstream the orifice
- Heat transfer at all interfaces.

5.4 Is the Capacity of the Flare System Utilised? (Step 2)

If the available flare system capacity is not utilised when combining all the simultaneous depressurisation rates for the entire system it should be considered to increase the depressurisation rate, i.e. increase the orifice size. This is an evaluation that needs to be considered for all the process segments being evaluated (i.e. as a minimum all segments within the same fire area).

In this context priority should be given to increase the depressurisation rates for the most hazardous segments, i.e. the segments with the highest pressures and/or the highest inventories and/or the most volatile liquid, and the thin walled segments.

Also note that systems that will have to be provided with PFP could reduce the depressurisation rate and, hence, "give room" for increase of the depressurisation rates for other segments.

If the flare system capacity is utilised above the actual capacity, the depressurisation rate needs to be reduced or the flare system capacity increased.

The maximum pressure gradient during depressurisation needs also to be checked for systems with requirements to a maximum pressure gradient during depressurisation |-dP/dt|, e.g. some compressor systems.

5.5 Calculation of the Wall Temperature Profiles for all Equipment and Piping (Step 3)

The time dependent temperature for all equipment and pipes in the process segment, not already covered with PFP, needs to be calculated.

The objective of this step in the calculation procedure is to calculate the weakening of the material caused by the fire and, hence, the local heat load should be applied for this calculation. The local heat load will depend on the fire scenario; see Chapter 4.6 and Appendix A.

All pipes means all pipe types with different diameter, pressure class and/or material quality. Note that the temperature profile for one particular pipe type usually is rather insensitive to the system pressure. This implies that the temperature profiles calculated for each pipe and equipment from the first iteration can be kept throughout the whole iteration procedure (step 3 can be omitted between the first and the last iteration to reduce the amount of calculations) for uninsulated pipes and equipment.

A final update of the temperature profiles shall, however, be performed for the final iteration with the applied PFP included.

Note: Step 1 (or 8) calculates the time dependent pressure for the total segment when the uninsulated area of the total segment is exposed to the global average heat load. Step 3 calculates the time dependent temperature of each pipe and component in the process segment while being exposed to the local peak heat load. Step 1 (or 8) and 3 should be calculated simultaneously. As a minimum the temperature calculation in step 3 should include the cooling effect of the inside fluid, i.e. the thermodynamic of the fluid during depressurisation/pressurisation.

5.6 Rupture Calculations (Step 4)

Based on the calculations performed in step 1 (or 8) (time dependent pressure) and 3 (time dependent material temperature) it can be found if any element (i.e. pipes or vessels) within the process segment will rupture.

The Material Rupture Criterion

The material rupture criterion can be based on limitations in either stresses or strains. When using a stress criterion, only the UTS value for the material is needed. When using a strain criterion the stress/strain relationship is required, and when large strains are expected true stress and true strain should be used. It is generally accepted that the strain criterion gives the most accurate results.

This version of the guideline does not give a specific recommendation for which approach should be used. However, Appendix C describes two methods, a stress based method and a method based on ductile burst pressure (strain method). Both methods are based on the temperature dependent UTS.

At a later stage in a project development it might be necessary to do a more detailed analysis of some of the system components due to high stress/strain utilisation. For these analyses a strain criterion should be considered.

Stress Calculations

Stresses in pressurised pipes/vessels will be dominated by three stress components, longitudinal, hoop, and radial stress. For thin, low pressure, pipes the radial component can normally be neglected. However, for thick pipes this component should be included.

For thin pipes equivalent stresses based on hoop and longitudinal stress components from thin shell theory can be used. For thick pipes this will give too low stresses, and is considered to be non conservative. It is therefore recommended that the equivalent stress based on Lamé theory is used for all pipes.

For further details see Appendix B and C.

5.7 Component Failure/Unacceptable Ruptures (Step 5)

If rupture in any of the components in the process segment is found to occur, the pressure criteria as well as the release criteria established in Chapter 4.7 need to be checked to determine whether this rupture can be accepted or not.

If all pipes and equipment in the process segment meet the acceptance criteria at the time of rupture (i.e. rupture pressure and mass of flammable fluid released from the section) the amount of fire insulation is sufficient. Go to step 7 for low temperature calculation. Otherwise go to step 6 and add insulation (go to step 8) or increase the size of the orifice (go back to step 1).

Other parameters to evaluate before adding more PFP are:

- Sectionalisation of process segments
- Increase the flare system capacity
- Change material quality
- Increase pipe/vessel wall thickness
- Upgrading of pipe class
- Change layout of equipment.

5.8 Passive Fire Protection (Step 8)

If a pipe or an item of equipment does not meet the acceptance criteria and it is not found possible to increase the orifice size or to improve other parameters, PFP needs to be added. Before deciding on which component to fire protect by applying PFP, the reason for the rupture should be established; is the rupture initiated by boiling (pressure build up) or is the rupture initiated by high local material temperatures?

If the rupture is a result of high local material temperatures, it is recommended to insulate the component that will rupture.

If boiling (and the pressure build up effect) is significant for developing the rupture then liquid filled pipes and the liquid section of the vessels should be prioritised for PFP.

It is recommended to first add fire insulation to the corrosion resistant pipe/equipment with the largest diameter. However, if there are pipes/equipment that are already insulated for other reasons (e.g. heat conservation, frost or noise protection, etc), these pipes/equipment shall be provided with PFP first.

The reason for insulating the corrosion resistant pipes first is to avoid insulation on materials that can corrode.

The reasons for prioritising large pipes are:

- Large diameter pipes are the most critical with respect to reaction forces, pressure wave and release rates when it ruptures
- Large diameter pipes will give most insulation area pr. meter of insulated pipe
- It is more cost efficient to paint and insulate large pipes than small pipes.

The iterative calculation should continue until the size of the orifice and the PFP requirements are optimised and the criteria for acceptable consequences at rupture are met, i.e.:

- Reduce the fire-exposed area by adding PFP
- Simulate a new pressure profile for the total segment
- Simulate a new temperature profile for each pipe and item of equipment (except pipes/ equipment already insulated). The temperature profile will not change much per iteration.

Due consideration should be paid to whether process piping should be treated as gas or liquid filled. This is illustrated in Figure 5.2.

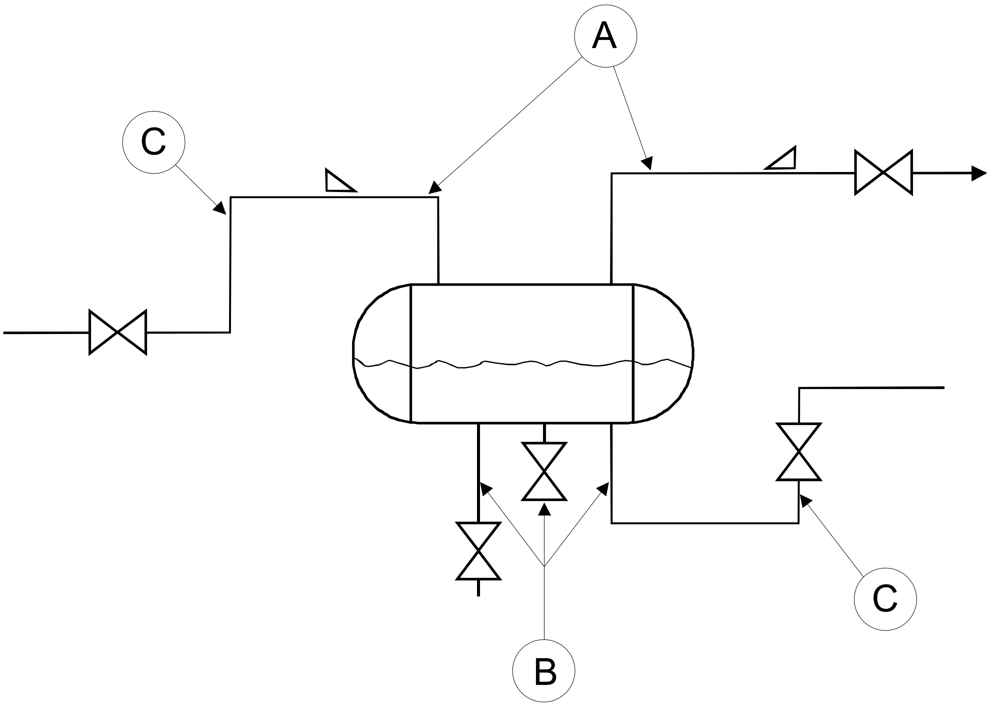

Figure 5.2: Principle Sketch of Piping Systems, which are considered Gas-filled, Liquid-filled or Semi Liquid-filled
A: Gas-filled lines
B: Liquid-filled lines
C: Semi liquid-filled lines

Semi liquid-filled lines, C, should be considered liquid filled when calculating P(t), i.e. including boiling effect. These lines should, however, be considered gas-filled when calculating T(t) due to the possible boil-off or gas pocket formation and, hence, faster temperature build-up of the non-wetted surface.

For liquid-filled lines communicating with liquid reservoirs > than 4,000 kg and which will be fed by gravity the integrity should be verified throughout the fire scenario.

In general flanges are recommended to be fire insulated. All flanges and valves located in pipes that need to be fire insulated shall normally be insulated. Flanges/valves located in pipes that are not insulated, should be evaluated individually and preferably be insulated. Flanges and valves in liquid lines communicating with liquid reservoirs > 4,000 kg or gas > 1,000 kg at the time of rupture should generally be insulated.

5.9 Low Temperature Check (Step 7)

Due to the Joule-Thomson effect when expanding a gas, the process segment in general and the tailpipe downstream the orifice in particular, may experience very low temperatures.

The low temperature shall be calculated and compared with the material quality in the system.

This depressurisation calculation shall be performed **without fire input** to the process segment **and with the applied insulation** (independent of type of insulation).

5.10 Deluge/Water Spray

Credit is generally not given by PSA to the effect of firewater in the above calculations. This is a conservative approach, as deluge/water spray would provide cooling and a reduction of the overall temperature (and flux) in a fire, ref. Chapter 4.6. An exception to the conservatism is the jet-impinged areas. In these areas it is less likely that there will be a reduction in the local heat load.

5.11 Parameters to adapt at various Project Stages

The procedure described in this guideline should be carried out whenever significant modifications are performed on a process plant. Such modifications could include

- New equipment, tie-ins or other modifications
- Increase of inventory
- Increase of operating or max. pressure
- Increase of operating temperature
- Changes in PFP
- Changes that might influence the potential fire scenarios in the area.

It should be recognised that during the various stages of a project development, the access to accurate design information and data will vary. Based on this, higher safety margins should be adopted in the early stages of a project to account for these uncertainties.

The prime objective in the early stage of a project development should be to avoid the use of PFP, i.e. prioritise fast, efficient and automatically initiated depressurisation to achieve adequate fire protection. For a new field development it is recommended to utilise only 80 % of the flare capacity in order to have some margin for uncertainties and future tie-ins or other modifications.

This implies that for a new design, and when depressurisation is the dimensioning design case for the flare system, the flare capacity should be increased by 20 % to cater for future modifications.

It is generally recommended to aim for a flare system design without bottlenecks i.e. avoids single components (e.g. K.O. drum or flare tip) with significantly lower capacity than the remaining system.

6. PROCEDURES FOR PROTECTION OF PIPE AND VESSEL SUPPORTS

This guideline does not focus on structural fire protection.

However, pipe supports, supports for pressure vessels or tanks containing combustibles as well as secondary structures supporting these functions may require PFP to maintain their integrity during a dimensioning fire.

The pipe and vessel supports shall maintain their function longer than the pipe/ equipment they are supporting.

It is generally recommended that:

- It should be verified that supports for pipes maintain their function until depressurisation of the related process segment has been completed, i.e. to below the criteria for rupture of the segment
- It should be verified that supports for pressure vessels and tanks maintain their function until depressurisation of the process segment in question has been completed
- Equivalent for secondary structures
- In particular focus should be on supports for pipes and headers in the depressurisation/flare system that are required to maintain the integrity throughout the fire.

7. REFERENCES

/1/ ISO 13702: "Petroleum and Natural Gas Industries - Control and Mitigation of Fires and Explosions on Offshore Production Installations - Requirements and Guidelines", 1999.

/2/ Norsk Hydro: "Best Practise Depressurisation and Fire Relief Design", NHT-0101512, December 2001.

/3/ NORSOK Standard S-001: "Technical Safety", Rev. 3, January 2000.

/4/ ASME VIII: "Boiler and Pressure Vessel Codes".

/5/ NPD: "Forskrift om utforming og utrasting av innretninger med mer i petroleums-virksomheten (Innretningsforskriften)", 3 September 2001. (NPD is from January 1. 2004 divided into two authorities where the PSA (Petroleum Safety Authority Norway) is responsible for Health, Safety and Environment).

APPENDIX A

HYDROCARBON FIRE CHARACTERISTICS

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A1. HYDROCARBON FIRE CHARACTERISTICS

Hydrocarbon fires in the process industry are a result of the uncontrolled escape of hydrocarbons. The reason for the release of the hydrocarbons can be many, and it may not be possible to include all possible scenarios. The hazards and characteristics of hydrocarbon fires will therefore normally be based on a limited number of typical scenarios. The selection of these typical scenarios should be based on evaluation of the following factors:

- Geometry of process plant
- Process (volume/mass of inventory, operating pressure etc.)
- Type of combustible hydrocarbon (gas, condensate, liquid or combination)
- Leak point, position and size
- Ventilation conditions
- Equipment and piping congestion
- Etc.

This evaluation is often done as a part of a QRA or similar to identify the typical hydrocarbon fires relevant to be dealt with for the actual process/process plant, and are often classified as liquid pool fires, jet fires (gas and oil), and confined jet and pool fires. In addition, other types of fires like running liquid fires, fireballs and cloud fires may be identified. Fireballs and cloud fires are often of short duration (less than 1-2 minutes) and will not have any significant thermal effect on structures and equipment, and are therefore not dealt with when designing fire protection.

In this context, the fire heat loads, size and duration are the main characteristics of the defined fire scenario we want to establish. This can be done either by calculations or by applying commonly accepted fire heat loads based on experience from experimental work etc.

A1.1 Methods for Calculation/Simulation of Fire Heat Loads and Sizes

Semi-empirical models can be used for open pool and jet fires and they will give reasonably good results for flame shape and size, but they are not suited for the prediction of flame temperatures and fire heat loads which have to be estimated based on experimental data. Heat fluxes to targets not engulfed by the flame can be calculated based on the surface emission power of the flame if the view factor between the flame and the target is known. Heat fluxes to targets engulfed by flames have to be estimated based on experimental data for the flame temperature and heat loads. Semi-empirical models are not suited for calculation of the fire characteristics of fires interacting with complex structures or confined fires.

CFD-models are the best-suited models to calculate heat fluxes and sizes for confined fires and fires interacting with complex structures. In principle, CFD-models will calculate close to real fire behaviour within the defined geometry including the process equipment. etc. The outcome from a CFD fire analysis can be a detailed distribution of the fire heat fluxes over the surface area of the process equipment. The result from such an analysis can be directly used as input to the response calculations (heating of objects like vessels, piping etc.).

CFD-models are so far only validated for a limited set of fire scenarios due to among other things, the lack of reliable and detailed experimental results suitable for comparison and validation purposes.

CFD-models represent a detailed and relatively expensive analysis of the fire scenarios. Together with the availability of validated and commercially available CFD-models, this often limits the use of such models in engineering projects.

It should also be noted that the number and types of scenarios in practical terms are infinite. This should be taken into account when using results from detailed calculations and it means that such calculations are more suited to determining the extension of different heat fluxes as a function of time rather than the particular localisation.

Standardised Fire Heat Loads

The alternative to calculating the fire characteristics for the selected fire scenarios is to use commonly accepted values for heat loads from typical fires. The NORSOK standard is such an example of guidance for heat loads from typical hydrocarbon fire scenarios experienced in large scale experiments for typical offshore and process plant environments.

Table A.1: NORSOK S-001 recommended Heat Fluxes from Hydrocarbon Fires

Type of fire	Initial heat flux density	
	Max. point loads	Average load
Pool fire (crude): Open or enclosed area, fuel controlled	150 kW/m^2	100 kW/m^2
Pool fire: Enclosed area, ventilation controlled	200 kW/m^2	130 kW/m^2
Jet fire	250 kW/m^2	

The NORSOK standard divides hydrocarbon fires into pool fires and jet fires where the pool fire can be ventilation or fuel controlled. Fuel controlled fires can in many situations be treated as fires in the open and will have much the same characteristics (temperature, size etc.). Ventilation controlled fires are fires in confinement (e.g. offshore modules) where the fire characteristics are closely coupled to the surroundings and often in interaction with complex structures.

The effect of the fires in terms of heat flux, is in NORSOK divided into maximum heat flux or load to a point and average heat load. Maximum point flux describes the situation where the fire or flame is engulfing the target, and the average heat load is associated with the total averaged heat flux to all surfaces, either within or outside the flame.

In this guideline it is recommended not to apply the NORSOK recommended heat fluxes, but instead use the proposed heat fluxes given in table A.3. The NORSOK heat fluxes were originally meant to describe the consequences for structures, fire partitions etc. from large fires and this justified high average heat loads in particular. New knowledge gained from recent experimental work (i.e. Blast and Fire Engineering for Topside Structures Project) and a number of CFD simulations, give reason for proposing alternative heat fluxes from small and medium hydrocarbon fires which are the fire sizes relevant for this guideline.

The heat fluxes in Table A.3 must be supplemented with data for

- fire size or area exposed to given heat fluxes
- fire duration
- ventilation conditions

in order to perform a proper evaluation of the consequences of the selected fires.

Fire Size/Exposed Surface Area

A process segment will have a total surface area, A (m^2), including all vessels, piping etc. which may be exposed to a heat flux from the fire. The heat flux may vary from zero to a maximum value distributed over the surface. The challenge is to decide or estimate the size of the areas that receive local high heat fluxes, A_{local}, the areas that receive the averaged heat flux , $A_{global,}$ and in some cases areas that receive zero or small (negligible) heat fluxes, A_{zero}.

The tabulated average heat flux for the global fire is the time and area average heat flux over this surface.

The area being exposed to the local heat load is of less importance since it is assumed to be much smaller compared to the global fire exposed area and for this reason does not influence the pressure profile during depressurisation. The tabulated average heat flux for the local exposure is the time average heat flux at one point during the fire exposure. All surfaces that can be exposed to the local heat load shall be calculated.

It is difficult to give general estimates of the fire size and, hence, the surface area exposed to different heat fluxes for confined fires and fires interacting with complex structures because the fire characteristics are very scenario dependent.

However, in this context it is important to note that there are two principal purposes for the calculation of heat transfer from the fire to the exposed equipment:

1. Calculate the total heat input into the process segment (wet/dry areas) in order to analyse the pressure profile in the process segment (global average heat flux should be used)
2. Calculate the maximum local heat input on the different items of equipment exposed in order to analyse the thermal response of the material (local effect/peak heat flux should be used).

A1.2 Fire Duration

The duration for pool fires can be estimated based on the total mass or volume of released liquid, area of the pool and burning rate for the actual liquid or fuel. The pool area can easily be estimated in case of no restrictions on the ground or floor or when the area is known due to bunds, trays etc. The burning rate for the actual fuel or liquid is tabulated in fire handbooks, and is typically 50 $g/s{\cdot}m^2$ for open pool fires. For enclosed pool fires the burning rate is usually higher due to enhanced radiation feed back to the pool. Fire engineering handbooks cover this topic..

It is important to notice that the duration of pool fires may be considerably longer than the actual liquid release period. This will be the case especially when the spill is collected in a tray or dike where the liquid is able to form a thick layer of liquid fuel. In general, the thickness of the remaining liquid layer after the stop of the release will determine the remaining period of pool burning. The surface of the spill and the drainage facilities will hence be of importance in this context.

Duration of Jet Fires

For pressurised vessels, pipes etc. containing gas, a leak normally will form a sonic gas jet. The mass leak rate is a function of the reservoir or vessel pressure and the leak rate will decrease as the pressure decreases. The duration of a leak above a certain size, e.g. 2 kg/s or 0.1 kg/s, depends on the leak area (initial leak rate), the amount of gas and evaporating liquid in the segment, time for activation of shut down and depressurisation, and the depressurisation capacity. The dynamic leak flow rate should be calculated by use of a depressurisation tool that can model simultaneous leak and emergency depressurisation. An alternative and less accurate method will be to assume choked flow and no flashing of liquid to gas as the pressure is reduced. It is then possible to find the maximum duration of a leak above a certain size, m_{crit}, by the equations given below.

The initial leak rate giving the longest duration, $m_{A,0}$ (kg/s), from a vessel with a total initial gas mass, m_0 (kg), under combined shutdown/blowdown, can be expressed as

$$(m_{B,0}/m_{A,0}) = \ln(m_{A,0}/m_{crit}) + (m_{B,0}/m_0)\cdot t_2 - 1 \qquad (1)$$

where

$m_{B,0}$	-	initial blowdown rate (kg/s)
m_{crit}	-	critical leak rate or cut-off rate (kg/s)
$m_{A,0}$	-	initial leak rate for leak with the longest duration (kg/s)
m_0	-	total initial mass in segment or vessel (kg)
t_2	-	time from fulfilled activation of shut down to activation of depressurisation (s)

m_0 is the initial amount of gas in the process segment. If the amount of gas flashing off as the pressure is decreased is significant compared to amount of initial gas, it should be estimated and included in m_0.

Equation (1) has to be solved by an iteration procedure. Equation (1) is valid only when the leak rate $m_{A,0} > m_{crit}$ at time t_2.

For the special case with assumed simultaneous shut down and depressurisation, eq. (1) can be expressed as

$$(m_{B,0}/m_{A,0}) = \ln(m_{A,0}/m_{crit}) - 1 \qquad (2)$$

The maximum duration t_{max} , for the initial leak rate with the longest duration, $m_{A,0}$, can be expressed as

$$t_{max} = t_1 + m_0/m_{A,0} \qquad (3)$$

where

t_1 = time from start of fire to shutdown of segment is fulfilled (s)

The initial blowdown rate, $m_{B,0}$, can be estimated for a normal blowdown case, as

$$m_{B,0} = (m_0 / t_f) \ln (p_0 / p_f) \qquad (4)$$

where t_f is the maximum time required to reach a certain pressure p_f in the system being blown down (t_f is a result from the depressurisation calculations).

A1.3 Ventilation Conditions

The ventilation conditions in the fire area will effect the fire characteristics (the highest temperatures/heat fluxes are observed for near stoichiometric fires), and it is important to estimate whether a fire is ventilation or fuel controlled.

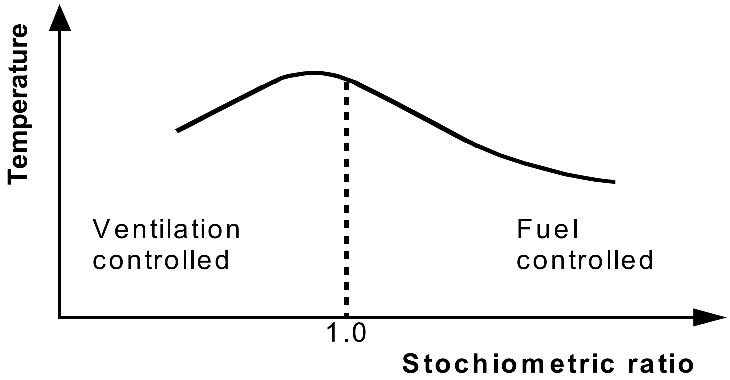

Figure A.1: Typical Relationship between Flame or Fire Temperature and Stoichiometric Air to Fuel Ratio

For an approximated evaluation a stoichiometric air to fuel ratio of 16 can be used (i.e. complete combustion of 1 kg/s of hydrocarbon requires 16 kg/s air). The ventilation conditions can be based on the design of the ventilation system or evaluated based on the requirements for air changes per hour for the actual area thus giving an estimate of the fuel supply rate that gives near stoichiometric combustion. In naturally ventilated areas, the fire may influence the ventilation conditions due to the fire induced flow of air, i.e. the ventilation will be more or less fire induced. This enhanced ventilation may increase the fuel supply rate that gives stoichiometric combustion.

As an example: A naturally ventilated offshore module of 5,000 m^3 (~ 6,000 kg air) is ventilated with 12 air changes per hour. The mass of air into the module will then be 20 kg/s and if complete combustion is required, ~ 1.25 kg/s hydrocarbon can be burnt. In this case, only fires rates below ~ 0.5 - 0.7 kg/s will be classified as fuel controlled fires. The effect of fire induced ventilation is disregarded in the example, and this effect will increase the fuel supply rate that can be termed fuel controlled ventilation regime.

Naturally ventilated areas offshore will normally have air change rates much higher (typically 50 - 200 air changes per hour), and the corresponding hydrocarbon leak rates giving stoichiometric combustion will be 3 to 12 kg/s (for a 5,000 m^3) module.

A1.4 Heat Transfer to Objects

A1.4.1 Definition of recommended Flame Model

The heat fluxes listed in Table A.3 for the different fire scenarios, are the total incident heat flux to the object at ambient temperature.

This total incident heat flux is here defined as

$$q_{total} = \sigma \cdot T_f^4 + h(T_f - T_{amb}) \qquad (5)$$

where

q_{total} - total incident heat flux to object (W/m^2)
σ - Stefan-Boltzmanns constant, $5.67 \cdot 10^{-8}$ ($W/m^2 \cdot K^4$)
T_f - flame temperature (K)
$\sigma \cdot T_f^4$ - the gross radiation heat flux (W/m^2)
$h(T_f - T_{amb})$ - heat convection to a cold surface (W/m^2)
T_{amb} ~ 293 K (20 C)

and h is either
$h_{jet\ fire}$ = 100 W/m^2K (see Chapter A1.4.2)
or
$h_{pool\ fire}$ = 30 W/m^2K (see Chapter A1.4.2)

and is used for calibration of the flame temperature, T_f given in Table A.2, that shall be used when calculating the heat absorption by real objects (pipes and vessels), see Chapter A1.4.2.

Table A.2: Calibration of flame temperature, T_f

	Jet fire		Pool fire
	For leak rates m > 2 kg/s	For leak rates m > 0.1 kg/s *)	
Local peak heat load	350 kW/m^2	250 kW/m^2	150 kW/m^2
Global average heat load	100 kW/m^2	0 kW/m^2	100 kW/m^2

*) This calculation is for an object located close to the leak source. The heat flux will vary during the fire duration, and 250 kW/m^2 is used as the average incident heat flux

A1.4.2 Absorbed Heat Flux by Objects using the recommended Flame Model

The incident radiation heat flux from a flame to an object can be expressed as

$$q = F \cdot \varepsilon_f \cdot \sigma \cdot T_f^{\ 4} \qquad (6)$$

where

q - incident radiation heat flux to object (W/m^2)
F - view factor between flame and object, $0<F<1$, (-)

ε_f - flame emissivity, 0.7 - 1.0 (-)
σ - Stefan-Boltzmanns constant, $5.67 \cdot 10^{-8}$ ($W/m^2 \cdot K^4$)
T_f - flame temperature (K)

In the case that part of the process segment is not engulfed by the fire, the incident radiation should be used. The contribution from convective heating will normally be negative (cooling) in this case unless hot combustion products are flowing over the object.

The heat transfer from the fire to the object is by radiation and convection.

This net heat transfer can be expressed as

$$q_{net} = \alpha_s \cdot \varepsilon_f \cdot \sigma \cdot T_r^4 + h(T_f - T_s(t)) - \varepsilon_s \cdot \sigma\, T_s(t)^4 \qquad (7)$$

where

q_{net} - net heat transfer to object (W/m^2)
ε_s - emissivity of the surface material (-)
α_s - absorptivity of the surface material (-)
ε_f - emissivity of flame (-)
σ - Stefan-Boltzmanns constant = $5.67 \cdot 10^{-8}$ ($W/m^2 \cdot K^4$)
T_r - radiation temperature of flame (K)
T_f - flame gas temperature (K)
$T_s(t)$ - surface temperature of the material (K)
h - convective heat transfer coefficient (W/m^2K)

The first term is the radiation heat from the flame absorbed by the surface, the second term is the heat convection from the flame gases and the last term is the re-radiation from the surface. It is recommended to keep the flame temperature constant during the analysis (see Chapter A1.4.1).

Recommended values (see also "Guidelines for the design and protection of pressure systems to withstand severe fires", Institute of Petroleum, 2002 and "Size depressurisation and relief devices for pressurised segments exposed to fire", Salater, Overå, Kjensfjord, CEP, September 2002. These references elaborate on the range of values):

ε_f = 1.0 (optical thick flames, thickness > ~ 1m)
α_s = 0.85
ε_s = 0.85
$h_{\text{jet fire}}$ = 100 W/m^2K
$h_{\text{pool fire/diffusive fire}}$ = 30 W/m^2K

The flame radiation temperature, T_r , can be set equal to the flame gas temperature, T_f, and selected according to recommendations given in Chapter A1.4.1 to obtain the absorbed heat flux for the chosen fire scenario.

A1.5 Proposed Heat Fluxes to be used

Experimental data from the latest major projects (JIP-Blast and Fire Engineering for Topsides Structures) on hydrocarbon fires relevant for offshore environments, show that the highest heat fluxes that may by expected are higher than the recommended values in NORSOK. These will be the heat fluxes termed as the max. point heat load in NORSOK. Since the local peak heat loads are to be used to determine the rupture temperature of the material, it is important that these fluxes are not underestimated.

The global averaged heat load is in this context, used for determining the total heat absorbed into the process segment during depressurisation. For small or medium sized fires it is reasonable to say that the NORSOK established values are too conservative due a number of reasons, particularly those relating to jet fires. Depending on the geometrical extension of the process segment, small and medium sized fires will only partly engulf the segment. Outside the flame the heat flux received by the pipes, vessels etc. will drop to a substantially lower level than the part of the segment engulfed by the flame.

The findings from the recent experimental works are supported by a number of CFD simulations performed for real offshore geometries with realistic oil and gas leak scenarios.

The fire properties will heavily depend on the degree of confinement as well as air supply (fuel/ventilation controlled). The focus in this guideline is primarily on fuel controlled fires (small fires that should not escalate to large fires). However, for facilities with limited ventilation, e.g. mechanical ventilation, even small fires might become ventilation controlled. This may influence the heat loads, in particular the global average heat loads.

It is important to note that high-pressure leaks of hydrocarbon liquids (oil/condensate) in many situations will burn as a liquid jet with much the same characteristics as a gas jet fire, and as a consequence should be treated as a gas jet fire. Generally liquid jet fires which are fed from a reservoir > 4,000 kg is not considered in this guideline since this is already defined as a large fire.

Based on process data (volumes, masses, pressure, temperature, fluid composition, initial leak rate, etc.) the duration of different leak rates should be estimated. For pool fires due consideration should be paid to the surface where the spill is accumulated and the drainage facilities in the area. Note that a pool fire may last substantially longer than the leak itself if liquids are allowed to accumulate. A liquid spill may also cause a run down of oil onto equipment causing a so called running liquid fire with a much higher burning rate per projected deck area than a liquid pool fire.

The new proposed total incident heat fluxes are shown in Table A.3

Small to medium sized fires are generally fuel controlled but in enclosures with limited air supply and in highly congested areas the fires may become ventilation controlled even for small supply rates of fuel. Such fires may result in higher global average heat fluxes than given in Table A.3.

Table A.3: Proposed Incident Heat Fluxes for Fuel controlled Fires for Protection of pressurised Systems. No Credit for Water Deluge is given

	Jet fire		Pool fire
	For leak rates m > 2 kg/s	For leak rates m > 0.1 kg/s *)	
Local peak heat load	350 kW/m^2	250 kW/m^2	150 kW/m^2
Global average heat load	100 kW/m^2	0 kW/m^2	100 kW/m^2

*) This calculation is for an object located close to the leak source. The heat flux will vary during the fire duration, and 250 kW/m^2 is used as the average incident heat flux

Comments to Table A.3

The given heat fluxes in Table A.3 are recommended heat fluxes for typical sized process segments i.e. separator segments.

The transient variation of the fire shall also be reflected, especially for jet fires. The transient behaviour due to decreasing leak rates will both influence the size of the exposed area and also the total heat flux to the process segment.

The global average heat load is used for calculating P(t) and is averaged over time and area over the entire process segment. Note that the global averaged heat load needs to be applied for both scenarios described below. If the process segment is very large (compared to the fire) a lower global average heat load might be justified.

Jet Fires

For a jet fire in an area containing several process segments, the dimensioning segment i.e. the segment giving the longest leak duration given a critical leak rate, m_{crit} (kg/s), must be identified.

For jet fires **two different scenarios** shall be analysed **separately**:

1. 350 kW/m^2 for a duration t' that corresponds to a leak rate, $m > m_{crit,}$ m_{crit}= 2 kg/s
2. 250 kW/m^2 for a duration t'' that corresponds to a leak rate, $m > m_{crit,}$ m_{crit}= 0.1 kg/s

where

t' is the time from start of the fire until the leak rate is reduced below m= 2 kg/s
t'' is the time from start of the fire until the leak rate is reduced below m= 0.1 kg/s

The above shall be interpreted as:

For jet fire scenarios:
Case 1) 350 kW/m^2 local heat load used in calculation of local steel temperature.
100 kW/m^2 global heat load shall be used for system pressure calculations. The duration for this scenario is t' seconds.

Case 2) 250 kW/m^2 local heat load used in calculation of local steel temperature.

0 kW/m^2 global heat load shall be used for system pressure calculations. The duration for this scenario is t'' seconds.

These two scenarios shall not be combined i.e. the local heat load of 350 kW/m^2 for a given time period t' shall not be followed by a local heat load of 250 kW/m^2 in the time interval t''-t' , but be analysed separately.

The reason that case 1 and 2 shall not be combined is that the flame from a specific leak will expose different locations during the initial phase (> 2 kg/s) and the late phase (< 2 kg/s). Hence, a specific location will be exposed to only one of the heat loads from a specific leak.

The difference in global heat load between small jet fires (global heat load 0 kW/m^2 for leak rates less than 2 kg/s) and medium jet fires (global heat load 100 kW/m^2 for leak rates larger than 2 kg/s), is due to the observation that small jet fires will have a limited flame volume compared to the typical size or extension of the process segment to be evaluated. This small flame volume result in a limited heat effect outside the flame region.

When calculating the jet fire duration, the worst case initial leak rate (i.e. the initial leak rate resulting in longest duration) should be used for each of the two scenarios. Credit should in this context be given to the effect of the depressurisation system. The jet fire duration can be calculated by the method given in Chapter A.1.2

Pool Fire

For pool fire scenarios:

- 150 kW/m^2 local heat load shall be used for the calculation of local steel temperature
- 100 kW/m^2 global heat load shall be used for system pressure calculations.

The duration for which a pool fire is evaluated should be equivalent to the time for which structural fire protection in the area is designed, normally this is defined in the DAL specification.

A1.6 Fire Calculations

An alternative approach to assess the heat fluxes and the size of the fire (exposed area), is to calculate realistic fire scenarios for the plant in question, e.g. by CFD modelling. If this approach is chosen, the methods and computer tools used should be validated. A justification for the chosen scenarios and an evaluation of the scenarios not handled should also be given.

APPENDIX B

MATERIAL DATA

TABLE OF CONTENTS

B1. INTRODUCTION

B1.1 General

This chapter presents material models and strength data for carbon and stainless steels typical for piping used in hydrocarbon processing plants. The models should be used in the burst analysis of pressurized pipes exposed to fire.

The following steel types are discussed:

Table B.1: Identification of Steel Types included

Steel type	Type/alloy	DIN	ASME	ASTM
Carbon steel	235LT	-	-	A-333/A-671
	360LT	-	-	-
Stainless steel (SS)	2205	1.4462	SA-790	A-790
SS (austenitic)	316	1.4401	A-358 316	A-320
SS (super-austenitic)	6Mo	1.4529	-	B-677

B1.2 Carbon Steel

Carbon steel, also called plain carbon steel, is a malleable, iron-based metal containing carbon, small amounts of manganese, and other elements that are inherently present. The definition of characteristic strength parameters are illustrated in Figure B.1

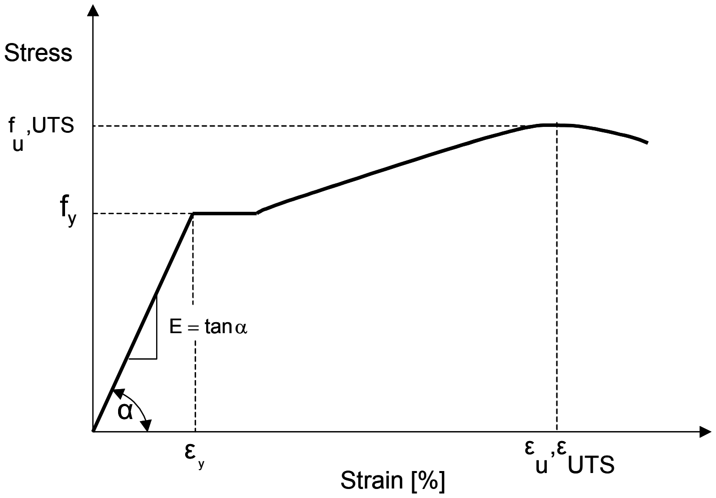

Figure B.1: Definition of Parameters for Stress Strain Relation for Carbon Steel

ε_u	is the strain corresponding to f_u
ε_y	is the strain corresponding to f_y
f_u	is the ultimate strength at 20 °C
f_y	is the yield strength at 20 °C
E	is the slope of linear elastic range at 20 °C
UTS	Ultimate Tensile Strength, equal to f_u

B1.3 Stainless Steel

Stainless steels are alloys of iron containing at least 10.5 % chromium and usually at least 50 % iron. The steel is stainless due to the fact that when exposed to air or water, a thin, stable, chromium-rich oxide film forms on the surface of these metals. This film provides a high degree of protection that reforms rapidly if damaged by scratching.

The controlled addition of alloying elements results in a wide range of material grades, each offering specific attributes in respect of strength, ability to resist certain atmospheric and chemical environments and to operate at elevated temperatures.

There are five basic groups of stainless steel, classified according to their metallurgical structure and thermo-mechanical treatment, i.e. the austenitic, ferritic, martensitic, duplex and precipitation-hardening groups. Martensitic and precipitation-hardening groups are normally not used in welded fabrications.

Austenitic stainless steels are the most commonly used stainless steels. They have an austenitic microstructure at room temperature and generally contain relatively high amounts of nickel. They have high ductility, are easily formed, are readily weldable and offer good corrosion resistance. They can only be hardened, i.e. made stronger, by cold-working.

Ferritic stainless steels contain relatively little nickel and have a ferritic microstructure. Ductility, strength, formability and weldability are not as good as in the austenitic steels. Although they are generally not as corrosion resistant as the austenitic grades, they are superior when considering stress corrosion cracking. As for the austenitic grades, they can be hardened by cold working.

Duplex stainless steels have a mixed microstructure and combine the best of the properties of the austenitic and ferritic groups. Compared to the austenitic group they have higher mechanical strengths, similar weldability, lower formability and similar or higher corrosion resistance especially with respect to stress corrosion cracking. They are hardened by cold working.

The stress-strain model for stainless steel is different from that of carbon steel. The initial part of the stress-strain characteristics become non-linear at an early stage and no clear yield point can be identified.

See Figure B.2 for the illustration of characteristic strength parameters of stainless steel.

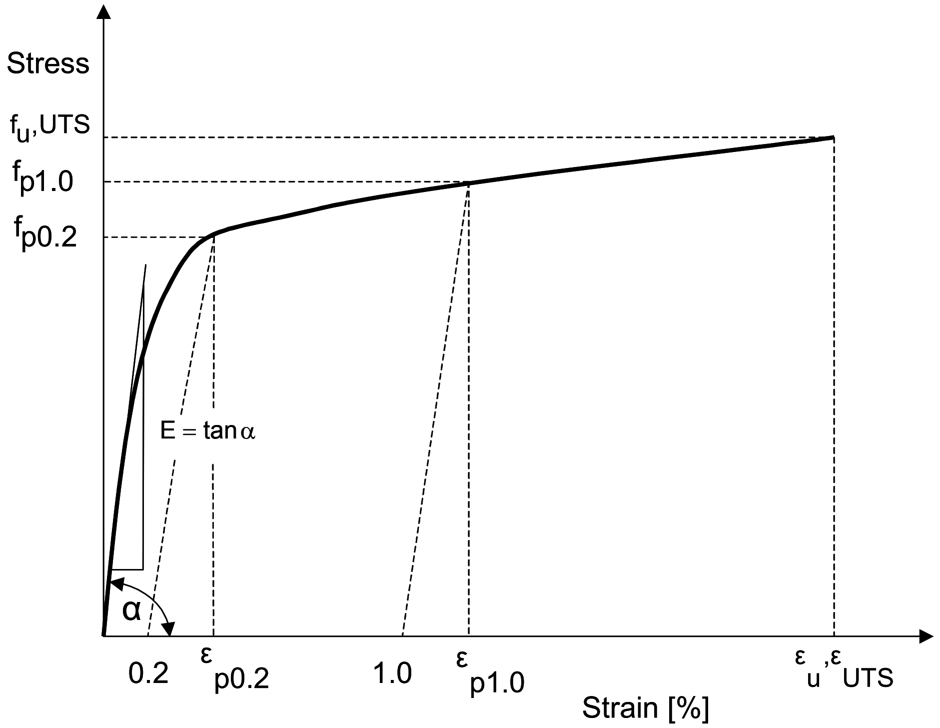

Figure B.2: Definition of parameters of the stress-strain relation for stainless steel

The characteristic parameters of stainless steel are defined as follows:

$\varepsilon_{p0.2}$	is the strain corresponding to $f_{p0.2}$
$\varepsilon_{p1.0}$	is the strain corresponding to $f_{p1.0}$
ε_u	is the strain corresponding to f_u
$f_{p0.2}$	is the 0.2 % proof strain strength at ambient temperature
$f_{p1.0}$	is the 1.0 % proof strain strength at ambient temperature
f_u	is the ultimate strength at 20 °C
E	is the slope of linear elastic range at 20 °C
UTS	Ultimate Tensile Strength, equal to f_u

B1.4 Description of Steel Material Characteristics for Rupture Analysis

A general reference to this chapter is ISO/CD 10400, Petroleum and Natural Gas Industries - Casing, Tubing and Drill Pipe - Equations and Calculations for Performance Properties. Draft version 2002.

In a “simplified” analysis using a stress criterion for determining pipe rupture, the only required material property is the UTS. When applying a strain based calculation, it will also require knowledge of the steel hardening, expressed by the hardening index n.

For the use of the steel material characteristics in the material non-linear (plastic) range, the stress-strain relation must be converted from the normally given engineering values, obtained from standard tests, into true stress-strain relations.

The true values of stress and strain can be calculated from:

$$\begin{aligned}\sigma &= \sigma_{nom}\left(1+\varepsilon_{nom}\right)\\ \varepsilon &= \ln\left(1+\varepsilon_{nom}\right)\end{aligned} \tag{1}$$

where:

ε	is the true strain
ε_{nom}	is the engineering (nominal) strain
σ	is the true stress
σ_{nom}	is the engineering (nominal) stress

For large strains the following relation can fit the true stress-strain relation:

$$\sigma_c = C\varepsilon^{\,n} \tag{2}$$

where:

$$C = \left(\frac{1}{n}\right)^{n} f_u \tag{3}$$

and

f_u	is the tensile strength, UTS, of a representative tensile specimen
n	is the hardening index used to obtain a curve fit of the true stress-strain curve derived from the uniaxial tensile test
ε	is the true strain
σ_c	is the Cauchy stress (true stress)

Discussion of the value of the hardening index n

For carbon steel the range of the hardening index n is normally between 0.06 to 0.14. For stainless steel the hardening index can be as large as 0.30. For burst calculations n should be obtained by a direct fit to the true stress-strain relation using Equation (2).

In Appendix C a rupture criterion called "ductile rupture criterion" is presented as an alternative criterion. This criterion requires that the hardening index n is known. The stress/strain relationship for the steel material must be known to be able to estimate the hardening index n by curve fitting as outlined above.

If sufficient information regarding the stress strain relation is not available, the following values for n can be used:

Carbon steel:	n = 0.10
Stainless steel:	n = 0.15

Figure B.3 illustrates the results from a pipe rupture calculation using the ductile rupture criterion presented in Appendix C for different D/t (outer pipe diameter/wall thickness) ratios and different hardening indexes n. The results are not very sensitive to the values of n.

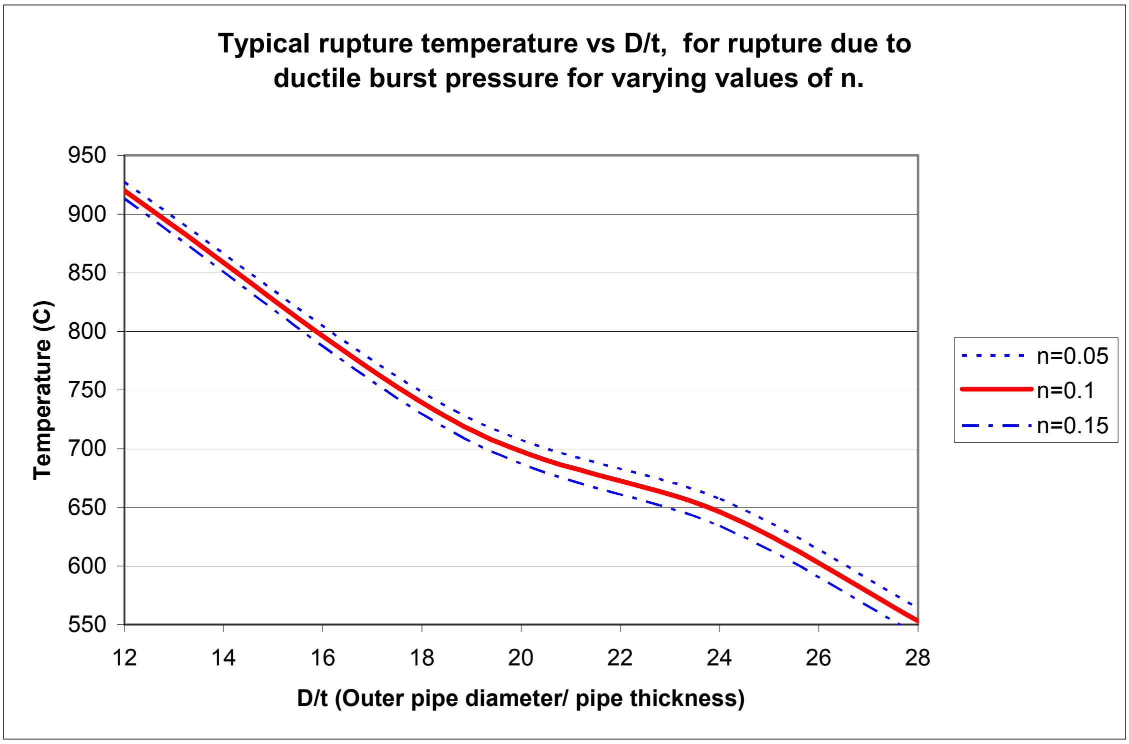

Figure B.3: Sensitivity of the hardening Index n for different Values of Pipe Diameter (D) to Wall Thickness (t)

B1.5 Steel Material Characteristics at elevated Temperature

At elevated temperature the strength characteristics of steel are reduced. This includes elasticity modulus, E, yield strength, f_y, proof strain strength, f_p, and the ultimate strength, f_u.

See Figure B.4 for the illustration of stress/strain effects at elevated temperatures.

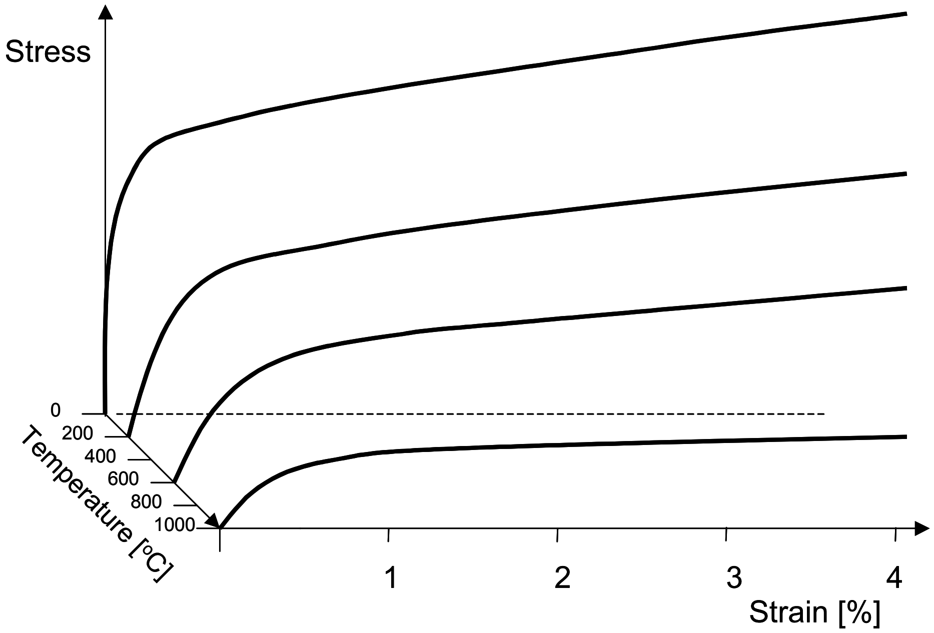

Figure B.4: Effects of elevated Temperature on the Stress/Strain Relation for Steel

In general this change in material properties follows the same pattern for all materials, but the variation between the different material qualities is significant. At a temperature of say 750 °C, the UTS for one material may have dropped to less than 15 % of the UTS at 20 °C, while an other material may have dropped to about 50 %. This lead to two important issues, which have to be utilised:

- The choice of material quality might have a significant influence on whether PFP has to be used or not
- The UTS reduction due to temperature is very different for different materials. It is therefore of major importance to know the temperature dependency for these materials over the complete temperature range (up to about 1,000 °C).

It is recognised that it can often be difficult to obtain accurate material data at high steel temperatures. It is therefore strongly recommended that these data are requested from the steel vendor when the pipes and vessels are ordered.

If the required material data is not available, the assumptions below can be used:

An estimated UTS(T) curve can be made based on an UTS(T) curve for a known material and the UTS at 20 °C for both materials. It is of major importance that these two materials are close in physical properties (same "family" of material (i.e. two different carbon steels or two different duplex steels)).

- If the actual material has a lower UTS value at 20 °C than the reference (known) material, the %-difference between the UTS values at 20 °C is kept at all temperatures, i.e. same shape of the known UTS(T) curve and the estimated UTS(T) curve

- If the actual material has a higher UTS value at 20 °C than the reference (known) material, the % difference between the UTS values at 20 °C is reduced linearly to zero between 20 °C and 1,000 °C.

If the UTS(T) curve is constructed according to the above assumptions, a value of 0.95 should be used for k_y when calculating the ATS, see Guideline Chapter 5.2 If, however, the actual and known materials are very close in physical properties a value of 1.0 for k_y can be considered.

A selection of some material data is included in this appendix.

B2. STEEL STRENGTH AT ELEVATED TEMPERATURES

Typical strength data at elevated temperatures for typical carbon and stainless steels are given in Table B.2 and Table B.3.

The recorded tensile strength at higher temperatures is very limited and must be treated with care. Additional testing to support the very limited test data and the established yield and tensile strength graphs in the temperature range above 500 °C is recommended.

Material data for temperatures above 500 °C should be considered as a requirement from the vendor when pipes are ordered.

A selection of some material data is included in this appendix.

Table B.1 Definitions of parameters used in the following tables and figures.

$R_{p0.2}$	The 0.2 % proof strain strength at **given** temperatures (stainless steels only)
R_m	The Ultimate Tensile Strength (UTS) at **given** temperatures
R_y	The Yield Strength at **given** temperatures (carbon steels only)

Table B.2: Typical Material Data at elevated Temperature. Stainless Steel

Temperature	**Type 22Cr Duplex**		**Type 316**		**Type 6Mo**	
[°C]	**$R_{p0,2}$ [MPa]**	**R_m [MPa]**	**$R_{p0,2}$ [MPa]**	**R_m [MPa]**	**$R_{p0,2}$ [MPa]**	**R_m [MPa]**
20	500	730	265	575	330	730
50	470	701	246	549	300	710
100	443	668	223	523	265	680
150	425	650	204	503	245	660
200	417	640	186	489	230	645
250	408	630	175	477	225	633
300	400	621	167	472	220	625
350	390	606	159	466	218	618
400	380	591	158	463	215	610
450	350	540	155	460	213	595
500	310	482	151	449	210	580
550	260	423	148	431	205	550
600	215	358	146	397	200	510
650	180	299	143	357	190	445
700	145	234	133	299	180	380
750	75	164	119	242	160	305
800		124	98	184	140	230
900		88	58	98	90	130
1000		69		70		90
1100		58		60		65

Table B.3: Typical Material Data at elevated Temperature. Carbon Steel

Temperature	**Type 235LT**		**Type 360LT**	
[°C]	**R_y [MPa]**	**R_m [MPa]**	**R_y [MPa]**	**R_m [MPa]**
20	280	420	380	545
50	269	414	365	537
100	252	407	342	529
150	241	403	327	523
200	235	397	319	515
250	232	391	315	507
300	228	382	310	496
350	227	378	308	491
400	221	370	300	480
450	207	353	281	458
500	179	308	243	400
550	155	252	211	327
600	125	189	170	245
650	98	139	133	180
700	66	92	90	120
750	36	59	49	76
800	28	46	38	60
900	24	38	33	49
1000				
1100				

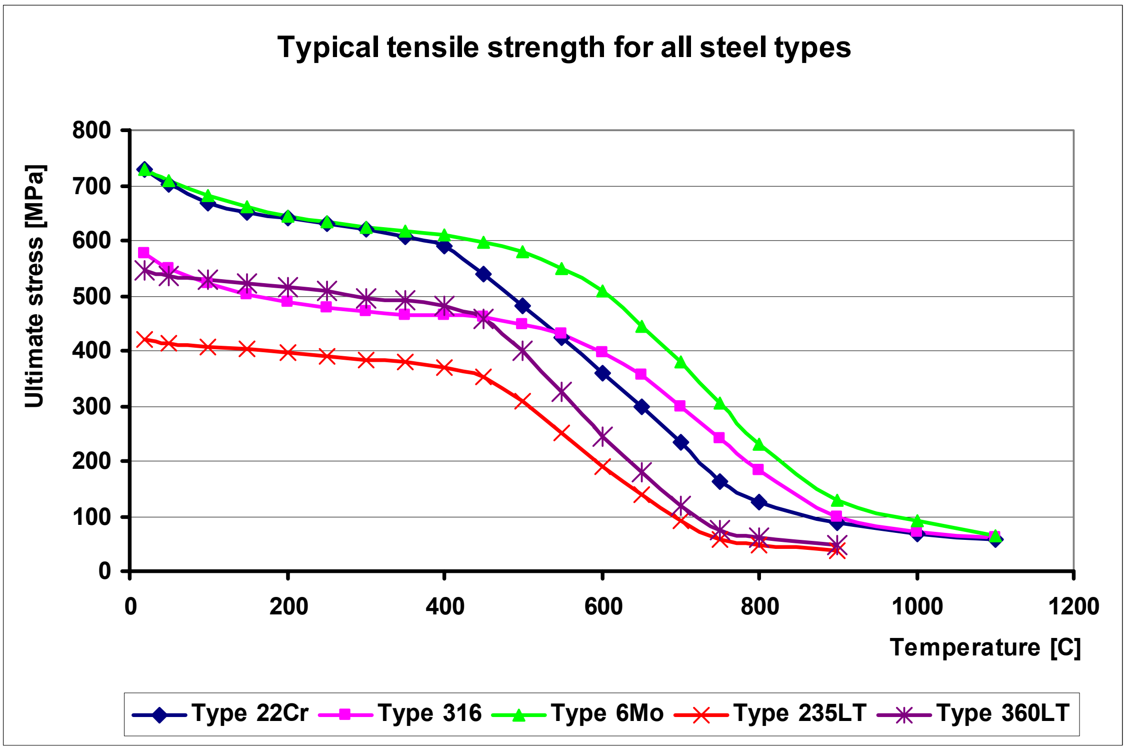

Figure B.5: R_m (UTS) for the tabulated Steel Types

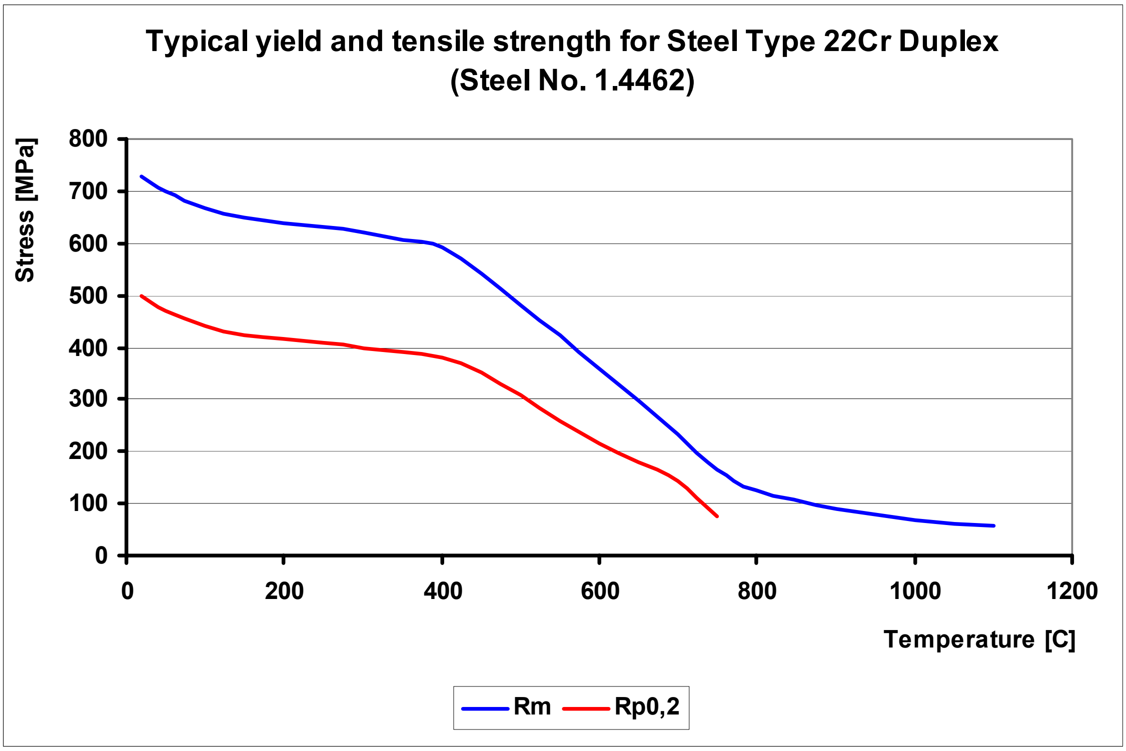

Figure B.6: $R_{p0.2}$, and R_m for Steel Type 2204

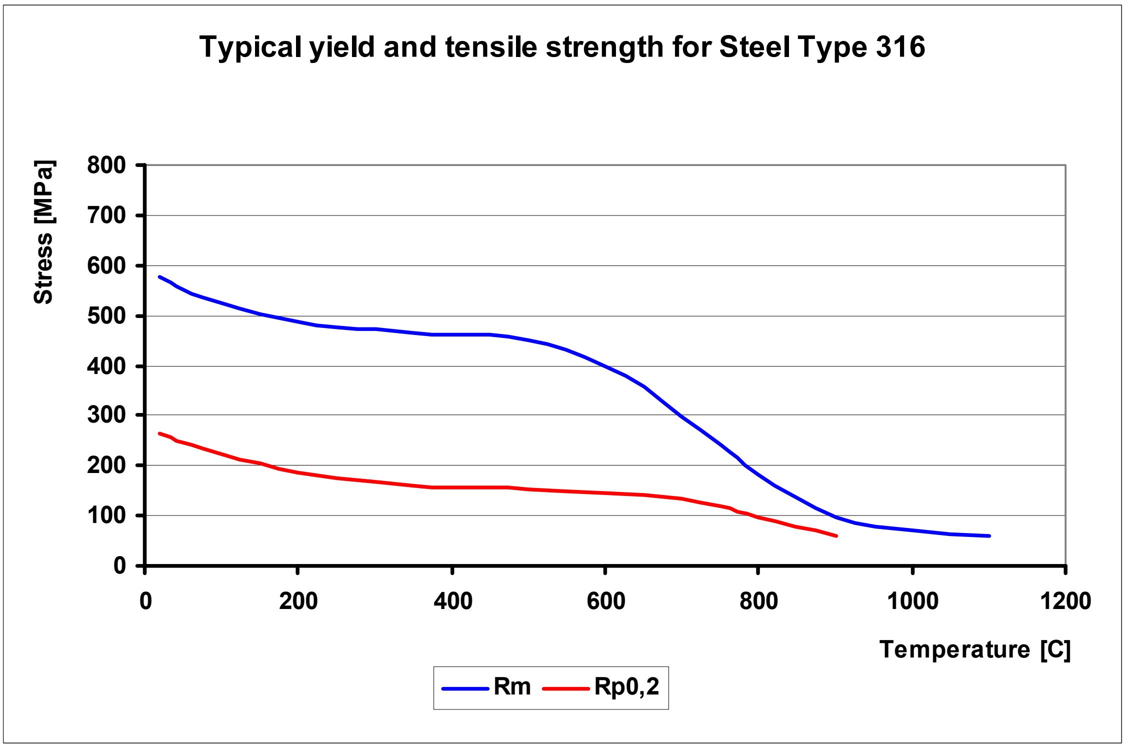

Figure B.7: $R_{p0.2}$, and R_m for Steel Type 316

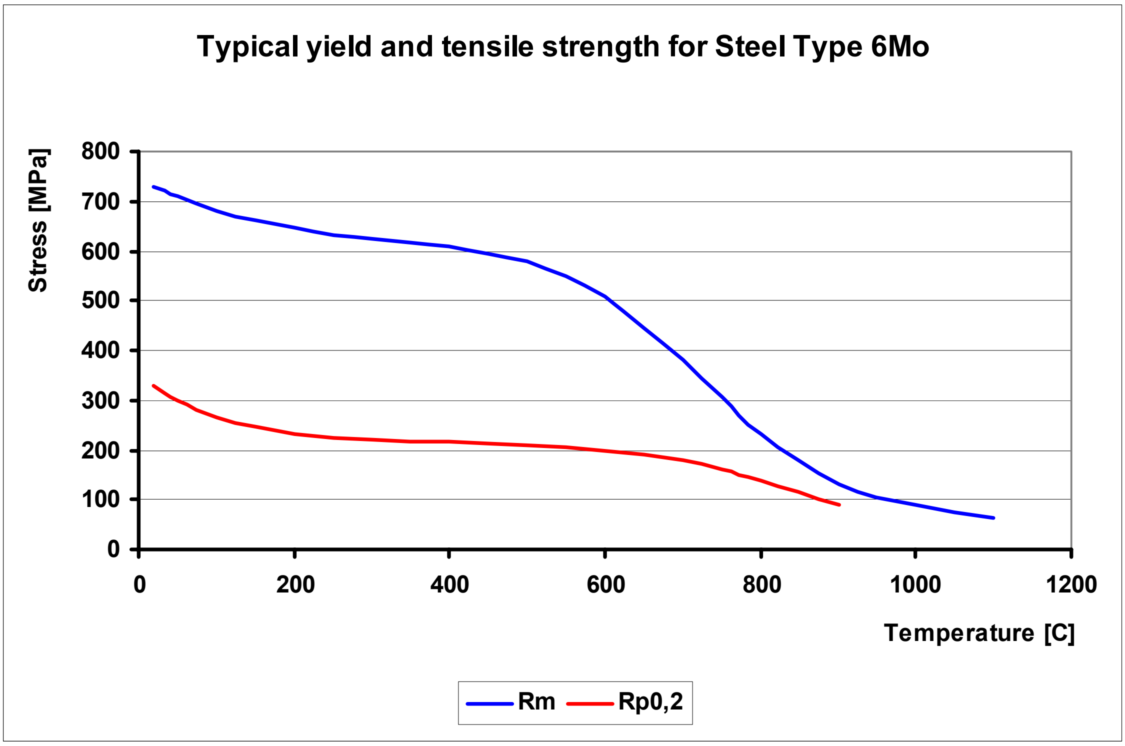

Figure B.8: $R_{p0.2}$, and R_m for Steel Type 6 Mo

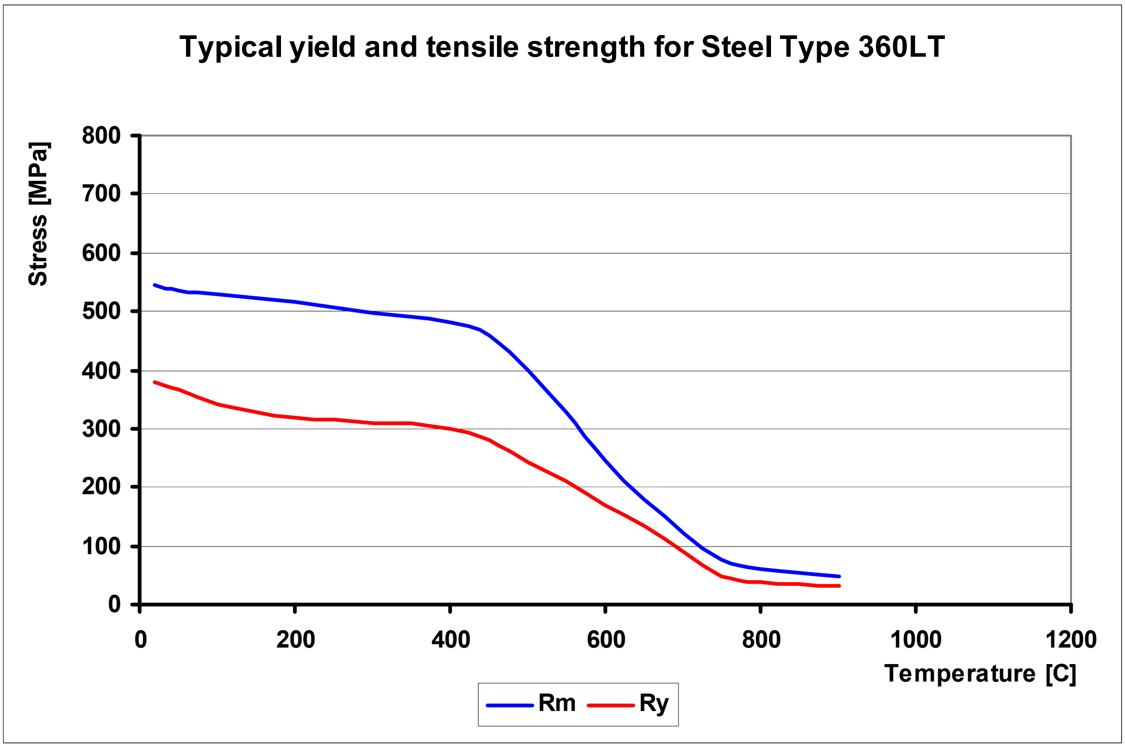

Figure B.9: R_y and R_m for Steel Type 360LT

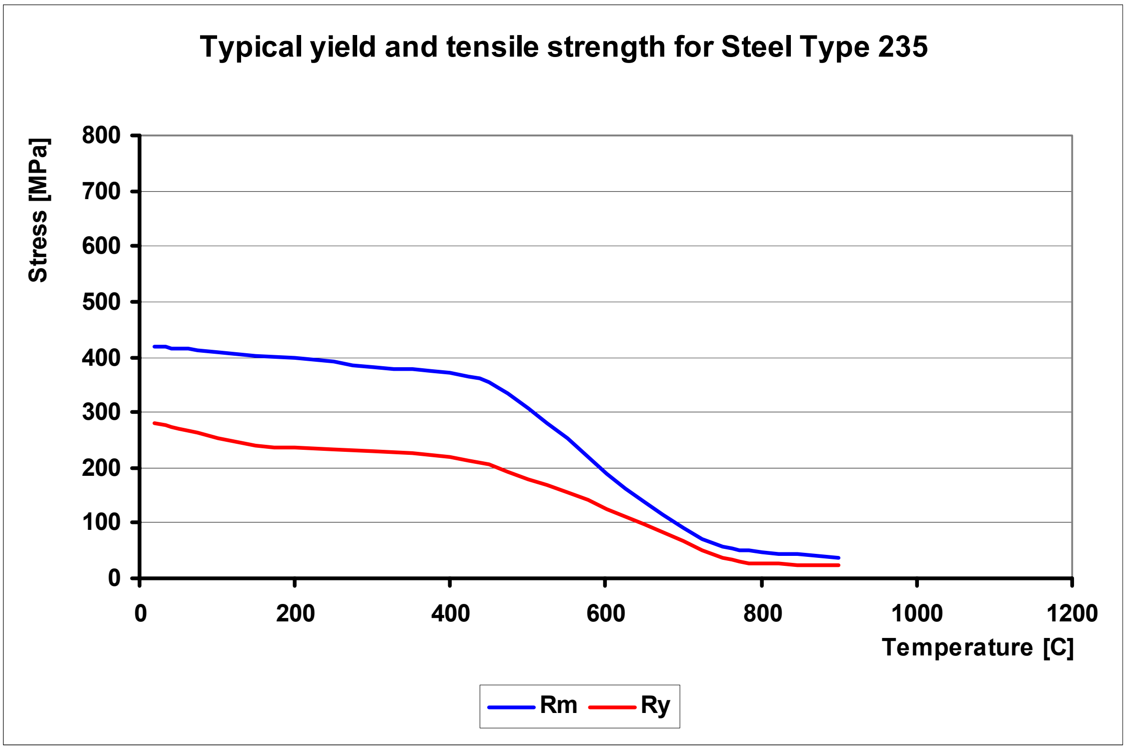

Figure B.10: R_y and R_m for Steel Type 235LT

B3. THERMO PHYSICAL PROPERTIES

Typical thermo physical properties for steel materials at elevated temperatures are given in Table B.4 and Table B.5.

Table B.4: Specific Heat Capacity for all tabulated Steel Types

Alloy	UNS S31600 Type 316	UNS S31803 Type22Cr Duplex	UNS S31254 Type 6Mo	Type 235 and 360
Temperature (ºC)	Specific heat capacity (J/kg,K)			
20	472	480	500	450
100	487	500	520	480
200	503	530	540	510
300	512	560	555	550
400	520	600	570	600
500	530	635	580	660
600	541	670	590	750
700	551	710	600	900
750	555	730		1450
800	559	750		820
900	565	790		540
1,000	571	840		

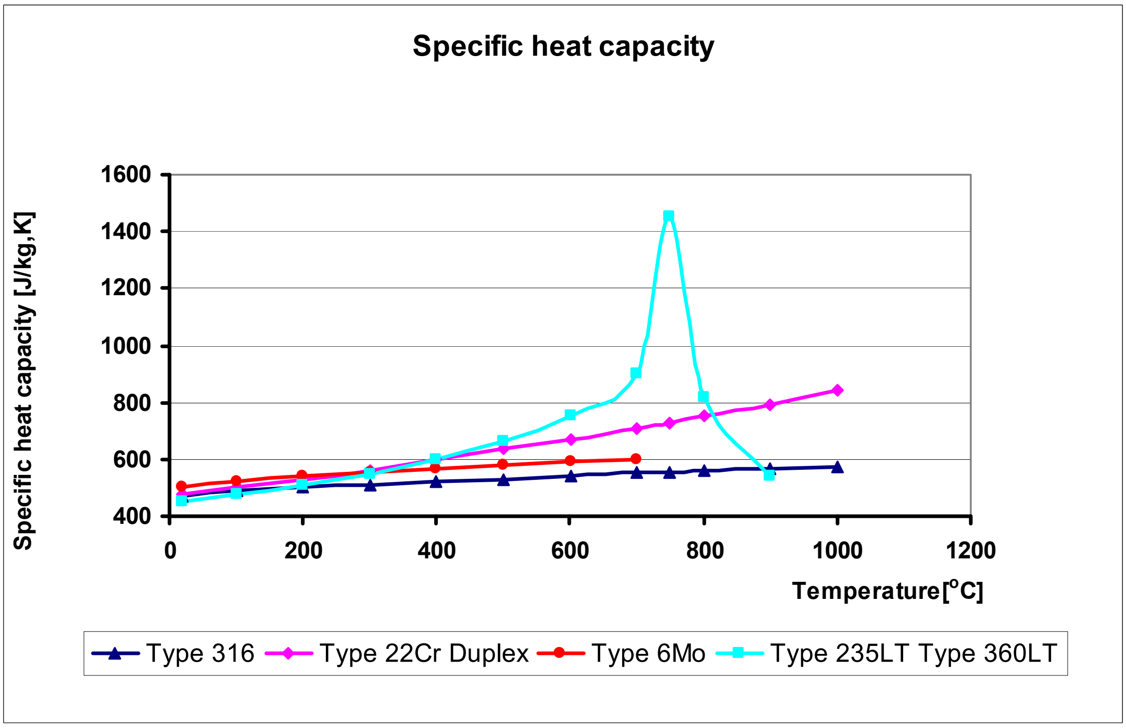

Figure B.11: Specific Heat Capacity

Table B.5: Specific Heat Conductivity for all tabulated Steel Types

Alloy	UNS S31600 Type 316	UNS S31803 Type22Cr Duplex	UNS S31254 Type 6Mo	Type 235	Type 360
Temperature (°C)	Specific heat conductivity (W/m,K)				
20	13,5	16,0	11,9	56,9	42,2
100	14,9	17,3	13,3	56,4	43,2
200	16,7	18,8	15,1	53,5	42,9
300	18,3	20,0	16,7	49,4	41,2
400	19,8	21,0	18,3	45,2	39,1
500	21,3	21,7	19,8	41,3	36,6
600	22,7	22,2	21,3	37,6	34,1
700	24,2	22,3	22,8	34	30
800	25,6		24,3	26	25
900	27,1		25,7		
1000	28,6		27,1	30	27

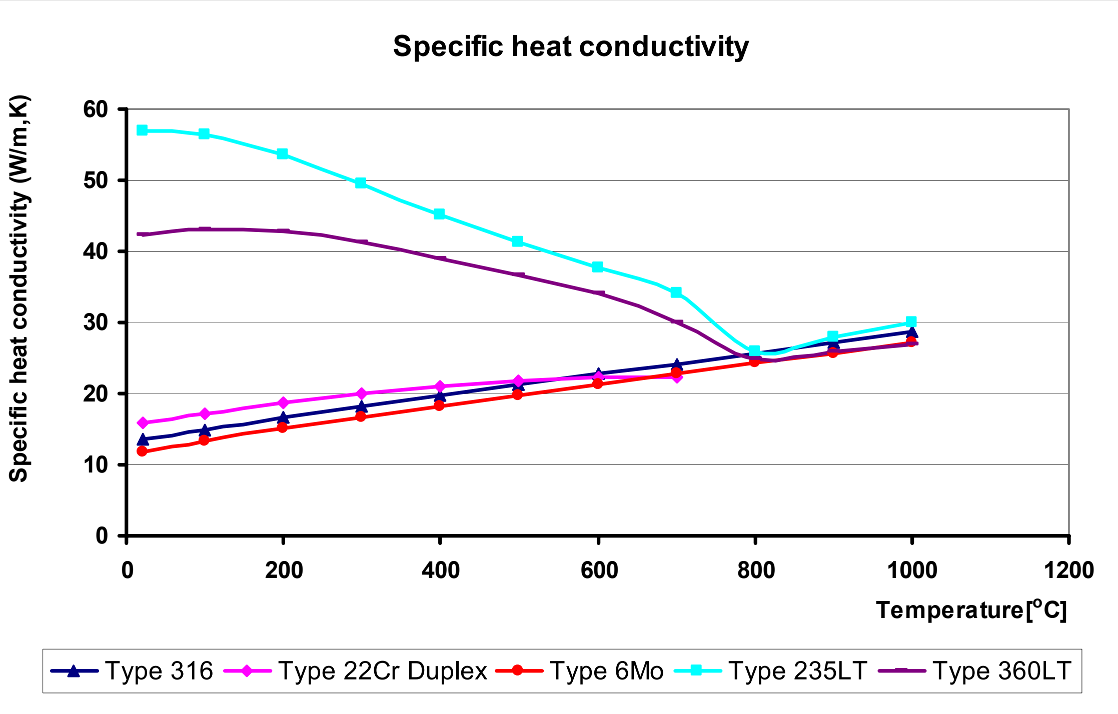

Figure B.12: Specific Heat Conductivity

APPENDIX C

RUPTURE CRITERIA

TABLE OF CONTENTS

C1. INTRODUCTION

C1.1 General

To determine whether a process element (pipe or vessel) ruptures or not, it is necessary to calculate the stresses in the element due to the loading, and compare this stress with the allowable stress for the element at the actual temperature.

The stresses in the element will depend on all loads, such as internal pressure, weight of fluid inside the element, own weight, weight from flanges and valves, thermal expansion, boundary constraints, etc.

The pipe and vessel material strength will depend on the material type and temperature, and therefore also on the possible fire scenario.

Due to uncertainties in the above data and uncertainties in calculation of stress, some considerations have to be made for the estimation of rupture pressure.

The fire relief and depressurisation design includes rupture calculations and has to be performed before the final layout of the process system is decided, in fact there might be many changes in the design prior to the final layout, and therefore a simplified method to evaluate the process element integrity is required.

This appendix gives guidance for simplified methods that can be used, and also discusses the considerations and implications of these methods.

Generally these methods will give good results for process elements where the internal pressure is high, Ref. /C-1/. For elements with low pressure, the methods are more uncertain due to the fact that other loading components than pressure become more important. As a final verification, a FEM (Finite Element Method) analysis should be considered for the most severe process elements.

C1.2 Selection of Rupture Criterion

This appendix includes two different rupture criteria. One is a stress criterion based on UTS, see Chapter C2.2, and the other is a ductile burst pressure (strain) criterion based on the UTS and the material hardening index "n", see Chapter C2.3. This guideline does not give any recommendations regarding which of these criteria that should be used, but some considerations are listed below.

- The stress-based criterion will usually be considered as the easiest to use
- If the ratio between the outer diameter and the thickness for a pipe is in the range of 15-20, the two criteria usually give about the same results regarding rupture temperature, see Figure C.1
- If the ratio between the outer diameter and the thickness for a pipe is less than 15, the stress criterion usually gives conservative results compared to the ductile rupture criterion
- If the ratio between the outer diameter and the thickness for a pipe is larger than 20, the stress criterion usually gives non conservative results compared to the ductile rupture criterion
- The ductile rupture criterion requires the material hardening index to be known. Usually this can be estimated based on the stress strain relationship, see Appendix B for further details.

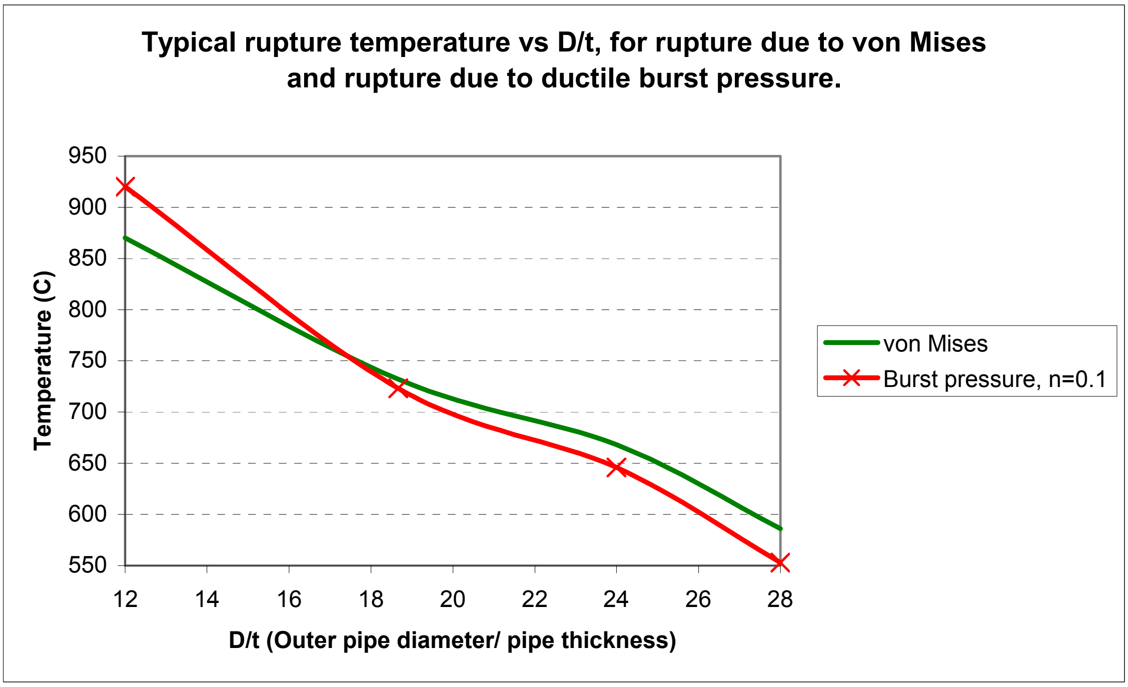

Figure C.1: Difference between Rupture Temperature based on Stress Burst and Burst Pressure for different Values of D/T

The time dependent pressure and steel temperature are results from the process calculations. Steel temperature in components not directly in contact with the inside fluid, such as flanges, bolts, valves and actuators, and supports must be considered separately.

If the allowable stress in any of these components is less than the actual stress at any time, or if the ductile burst pressure is less than the actual pressure, depending on the chosen criterion, a rupture must be assumed. If this rupture is found to be unacceptable according to the criteria outlined in Chapter 4.7 of this Guideline, the options, outlined in step 6 in the iteration procedure described in Chapter 5 in this Guideline, should be used.

C1.3 Wall Thickness

The production tolerances for pipe wall thickness allow for variation in wall thickness that has to be taken into account. A widely used tolerance is +/-12.5 %. Today's productions methods allow for a much smaller tolerance and therefore most pipes are delivered with tolerances close to -10 %, i.e. the produced wall thickness can as a consequence be 10 % below the nominal wall thickness. To ensure that the pipe rupture calculations are conservative, it is recommended that the following wall thickness variations are used in the calculations:

- When doing the stress calculations, use the nominal thickness minus both the production tolerance and the corrosion allowance, i.e. the calculation should be performed for the thinnest possible wall. The corrosion allowance is normally 3 mm, but if low corrosion is documented a smaller value can be used

- When doing pressure profile calculations (using the global average heat load), use the nominal thickness minus the production tolerances. This means a reduction in the system thermal mass compared to the nominal thickness. A reduced pipe thermal mass will result in a more rapid heat-up of the pipe and consequently the fluid. This will increase the pressure during depressurisation and relief. Here it is assumed that the corrosion is not global and hence is not influencing the total system mass.

- When calculating the local steel temperature in the pipe (using the local peak load), use the nominal thickness minus both the production tolerances and the corrosion allowance. It is here assumed that the local heat load is exposing the thinnest wall.

- If it is chosen to calculate the longitudinal stress, σ_a , Ref. Chapter C2.1, due to external forces instead of setting this stress component to 30 MPa, ref. Chapter C2.2.3, the nominal wall thickness should be used when calculating the pipe weight (no reduction in wall thickness, consequently the heaviest pipe)

- Pipes with welding seams may have a "welding factor" < 1.0, but based on recommendations given in EN-13480-3 Metallic Industrial Piping, 2002 edition, the factor is set to 1.0.

The corrosion allowance should be verified by the material discipline. Reduction of the corrosion allowance will have significant impact on the stress calculations, and hence on the time to rupture for thin wall pipes (design pressure < 100 bar), but less impact on thick wall pipes, Ref. /C-1/.

The production tolerance is often fully utilised for the expensive stainless steels and for high alloy materials, whereas for cheaper materials such as carbon steel, the production tolerance is often not utilised by the pipe fabricator. Hence, the nominal wall thickness could be reduced by less than the maximum production tolerance for some materials.

C2. PIPES

The following method can be used for calculation of stress in pipes, although a more accurate method (FEM analysis) is recommended if practical and for verification purposes.

A general reference for this chapter is ISO/CD 10400, Petroleum and Natural Gas Industries - Casing, Tubing and Drill Pipe - Equations and Calculations for Performance Properties, draft revision 2002.

C2.1 Stresses in Pipe

The hoop stress is caused by the pressure inside the pipe, and will be the dominant stress component at high pressure. The longitudinal stress is a sum of axial stress due to pressure ("end cap forces"), stress due to the weight of the pipe/valves/fittings/ branch pipe, etc., support constraints and thermal elongation of the pipe, and will be the dominant stress component at low pressure.

For a pipe exposed to internal pressure, the radial and circumferential (hoop) normal stresses in the pipe are given by Lame’s equations

$$\sigma_r = \frac{\left(pd^2 - \frac{pd^2D^2}{4r^2}\right)}{D^2 - d^2} \tag{1}$$

$$\sigma_h = \frac{\left(pd^2 + \frac{pd^2D^2}{4r^2}\right)}{D^2 - d^2} \tag{2}$$

$$\sigma_l = \frac{pd^2}{D^2 - d^2} \tag{3}$$

where:

D	is the specified outside diameter of the pipe
d	is the inside diameter of the pipe, $d = D - 2t$
p	is the internal pressure
r	is the radial coordinate
t	is the wall thickness of the pipe
σ_l	is the longitudinal stress due to end cap forces
σ_h	is the circumferential or hoop stress
σ_r	is the radial stress

See Chapter C1.3 regarding the diameters and the wall thicknesses to be used in these stress calculations.

The gravitational force field, along with other environmental loads (e.g. hydrostatic pressure on shoulders, changes in temperature and pressure, landing practice) give rise to an axial force, F_a, and a bending moment, M.

$$\sigma_a = \frac{F_a}{A_p} + \frac{M}{W} \tag{4}$$

where

σ_a Is the longitudinal stress due to the external force
A_p is the area of the pipe cross section, $A_p = (\pi / 4)*(D^2 - d^2)$
W Is the section modulus for the pipe
F_a is the axial force
M Is the maximum bending moment along the pipe

The maximum resulting axial stress, σ_{ax}, across any cross section is

$$\sigma_{ax} = \sigma_l + \sigma_a \tag{5}$$

C2.2 The Rupture Stress Criterion

C2.2.1 Yielding of Pipe Exposed to Pressure and Axial Stress

The von Mises stress for a pipe exposed to pressure and axial stress is

$$\sigma_e = \left(\sigma_r^2 + \sigma_h^2 + \sigma_{ax}^2 - \sigma_r\sigma_h - \sigma_r\sigma_{ax} - \sigma_h\sigma_{ax}\right)^{\frac{1}{2}} \tag{6}$$

where:

σ_{ax} is the axial stress
σ_e is the equivalent stress
σ_h is the circumferential or hoop stress
σ_r is the radial stress

The onset of yield is defined as

$$\sigma_e = f_y \tag{7}$$

where

$\sigma_e < f_y$ corresponds to elastic behaviour, and
f_y is the yield strength of a representative tensile specimen

Substituting Equations (1), (2) and (5) into (6), and using the yield criterion (7), the yield surface is given by:

$$f_y^2 = \left(\frac{pd^2}{D^2 - d^2}\right)^2 + 3\left(\frac{p\,D^2}{D^2 - d^2}\right)^2 + \sigma_{ax}^2 - 2\,\frac{pd^2}{D^2 - d^2}\,\sigma_{ax} \tag{8}$$

By substituting Equation (3), (5) into (8) the yield surface is expressed by:

$$f_y^2 = 3\left(\frac{p\,D^2}{D^2 - d^2}\right)^2 + \sigma_a^2 \tag{9}$$

C2.2.2 The rupture stress criterion

In Capter C2.2.1 the von Mises stress criterion is described based on the elastic material behaviour, and yielding is said to take place when $\sigma_e = f_y$. In this guideline we have further assumed that the von Mises formulations for equivalent stress (Eq. 6) are valid for stresses above the yield stress limit i.e. up to the ultimate tensile strength.

Rupture is defined when

$$\sigma_e = ATS = f_{u,T} \times k_s \times k_y \tag{10}$$

where

$f_{u,T}$ = ultimate tensile strength (UTS) at elevated temperature

and ATS is UTS multiplied by the safety factors as described in Chapter 5.2 of this Guideline and

$$\sigma_e^2 = 3\left(\frac{p\,D^2}{D^2 - d^2}\right)^2 + \sigma_a^2 \le ATS \tag{11}$$

is the equivalent or applied stress (Ref. Eq. 9).

C2.2.3 Assumptions

Unless more accurate methods are used, the above equations can be used for all piping, including bends. The additional longitudinal stress component, $\sigma_{a,}$ should be calculated, taking all the loading from the weight of the pipe/valves/fittings/branch pipe etc. into account. The longitudinal stress component, $\sigma_{displ,}$ representing support constraints and thermal elongation of pipes should be considered as part of σ_a. However, when the material starts to yield this stress component usually disappears, and σ_{displ} can be neglected.

As this can be rather cumbersome some simplified assumptions can be made:

- σ_a = 30MPa will in many situations represent a conservative assumption
- The maximum normally recommended pipe span (distance between pipe supports) will give a 8 mm deflection between supports for pipe sizes DN50 and smaller, and 10 mm deflection for pipe sizes DN80 and larger due to pipe weight and weight of inventory
- If the pipe span is loaded with weights from valves/fittings/branch pipe etc, σ_a, should be calculated instead of using the proposed 30 MPa. This calculation should include all external loads, and the longitudinal stress component found should be used as value for σ_a even if it is smaller than 30 MPa.

When a pipe stress model is available, it is recommended to set the pipe stress model's pressure term to zero to get an idea of the longitudinal stress component.

Normally the stress related to thermal expansion can be neglected due to relaxation at yield stress. However, in stiff piping geometries special considerations have to be made. In some situations thermal expansion can cause large bending moments in the piping system including flanges. These bending moments can create leakages even if the connection itself is covered with PFP. This leak 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.

As can be seen from Figure C.2 the three stress theories give somewhat different stresses for varying D/t ratios (outer diameter to wall thickness). The deviation is of the order 3 to 10 % between a von Mises formulation based on thin shell theory used in revision 1 of this guideline and a von Mises formulation based on Lamé theory where the Lamé based von Mises is the more accurate formulation. The thin shell theory will give slightly less conservative results than the Lamé theory.

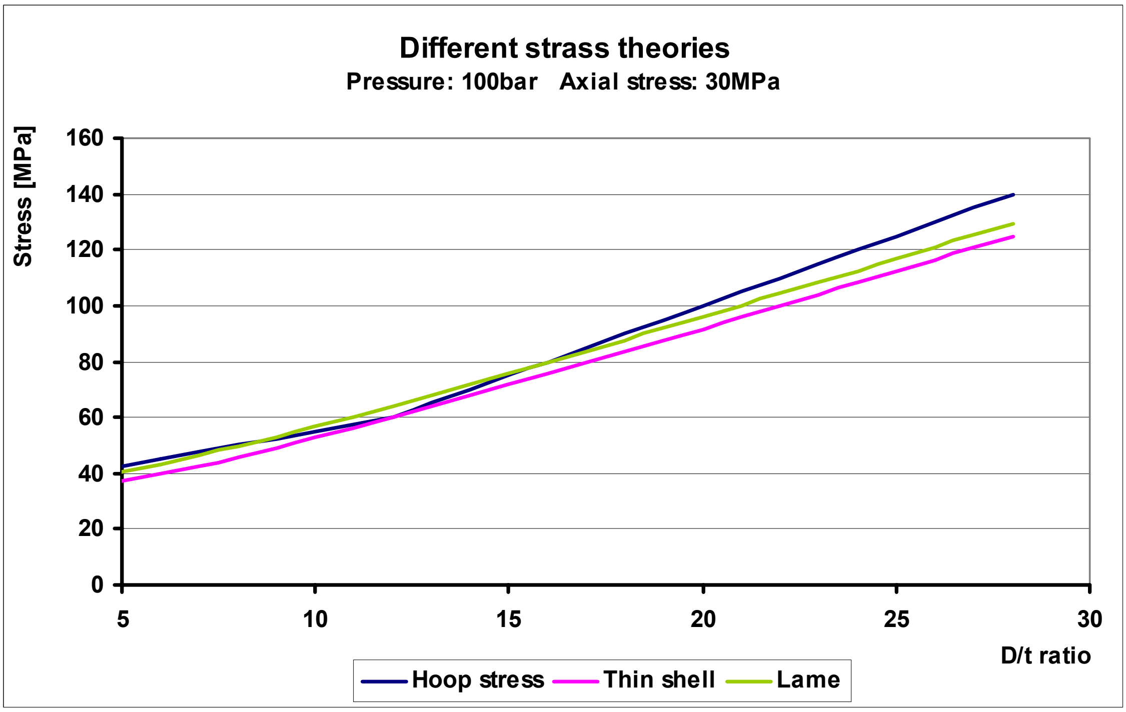

Figure C.2: Comparison of different Stress Theories as Function of the D/t Ratio (outer Diameter to Wall Thickness)

C2.3 The Ductile Burst Criteria

C2.3.1 Pipe exposed to Internal Pressure

The burst criterion for pressurised pipes is based on equations given in ISO 10400, *Petroleum and Natural Gas Industries - Casing, Tubing and Drill Pipe - Equations and Calculations for Performance Properties*.

For a pipe exposed **only** to internal pressure the burst pressure is

$$p_{iR} = 2k \frac{t}{D-t} f_{u,T} \tag{12}$$

where the correction factor, k, based on pipe deformation and material strain hardening is:

$$k = \left[\left(\frac{1}{\sqrt{3}} \right)^{1+n} + \left(\frac{1}{2} \right)^{1+n} \right] \tag{13}$$

and

t is the thickness of the pipe
D is the specified outside diameter of the pipe
$f_{u,T}$ is the ultimate strength at elevated temperature
n is the hardening index, ref. Chapter B1.4

The value of the correction factor, *k*, for different hardening index, *n*, is given in Figure C.3.

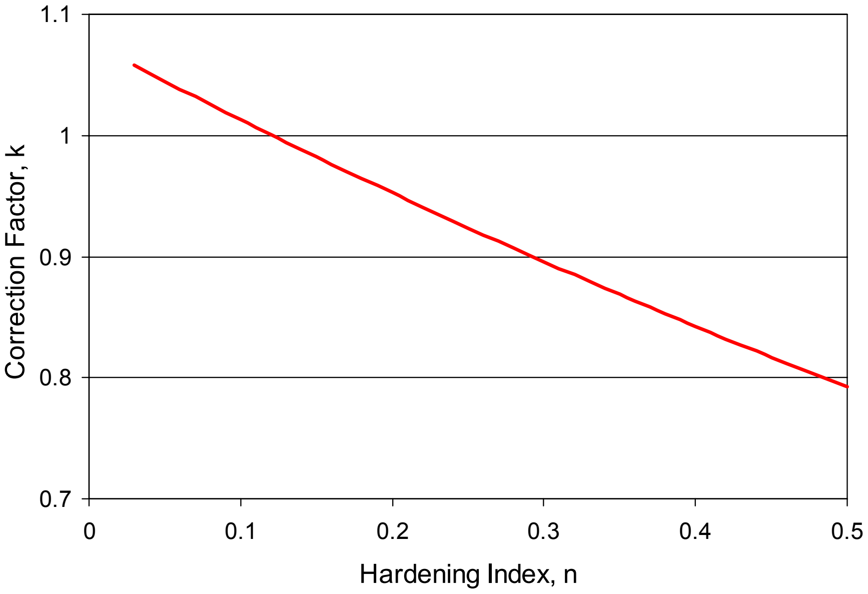

Figure C.3: Values of the Correction Factor, k, as function of Hardening Index n

C2.3.2 Pipe Exposed to Internal Pressure and Axial Stress

The ductile rupture strength Equation (12) was developed based on an end-capped pipe, where the axial tension is determined by the internal pressure acting on the closed inner pipe surface area. This is a special case of a more general situation where a pipe may reach a maximum internal pressure load, the rupture load, under the simultaneous action of arbitrary external pressure and arbitrary axial tension or compression. The combined loads together determine when the pipe is going to yield and how it will plastically deform towards the point of rupture. A fundamental criterion when this rupture load is attained can still be expressed, but this will now be a more involved equation governed by the formulation of yield surface in terms of axial stress, radial stress and hoop stress.

In the presence of an axial tension or compression stress different from capped-end conditions, the general equation for ductile rupture is

$$p_{iRa} = \min\left[\frac{1}{2}\left(p_{iM} + p_{iT}\right), p_{iM}\right] \tag{14}$$

with

$$p_{iT} = p_{ref} \tag{15}$$

$$p_{iM} = \frac{\left(k_L + k_M^{0,5}\right)}{k_N} p_{UTS} \tag{16}$$

where

$$p_{UTS} = 2\frac{t}{D-t} f_{u,T} \tag{17}$$

$$p_{ref} = \frac{1}{2}\left(p_{ref\,M} + p_{ref\,T}\right) \tag{18}$$

$$p_{refM} = \left(\frac{2}{\sqrt{3}}\right)^{1+n}\left(\frac{1}{2}\right)^{n} p_{UTS} \tag{19}$$

$$p_{refT} = \left(\frac{1}{2}\right)^{n} p_{UTS} \tag{20}$$

$$k_M = k_L^2 - k_N k_O \tag{21}$$

$$k_L = \left(\frac{2}{3}\right)\left[1 - 2t\frac{e^{-n}}{D-t}\right] e^{-n}\left\{\frac{\sigma_a}{f_{u,T}}\right\} \tag{22}$$

$$k_N = 1 + \left(\frac{1}{3}\right)\left[1 - 2t\frac{e^{-n}}{D-t}\right]^2 \tag{23}$$

$$k_O = \left(\frac{4}{3}\right)\left\{\frac{\sigma_a}{f_{u,T}}\right\}^2 e^{-2n} - \left(\frac{p_{ref\,M}}{p_{UTS}}\right)^2 \tag{24}$$

and

p_{iR}	is the internal pressure at ductile rupture
p_{iRa}	Is the p_{iR} adjusted for axial load
$f_{u,T}$	is the ultimate strength at elevated temperature
σ_a	is the longitudinal stress due to the external force, see Chapter C2.1

C3. VESSELS

In the design process for a new plant where the need for PFP is evaluated, the detailed layouts of the vessels are normally unknown. Specifically nozzles and other "disturbances" to the smooth surface are unknown. Based on this a vessel can normally be checked for rupture due to fire exposure using the same method as for the pipes, i.e. check rupture against the equivalent stress.

A fire exposed vessel which is partly filled with liquid and where the fire exposes the wall outside the liquid gas surface, will have large wall temperature gradients due to the different heat transfer to the different fluids and due to different temperatures in the different fluids, i.e. the wet inner wall will be much colder than the dry inner wall.

When the design of the vessel, including nozzles and other disturbances to the smooth surface is finalised, a non-linear FEM analysis should be considered for verification purposes. A FEM analysis will usually result in a longer time to rupture, since such an analysis includes the stress relaxation when the material starts to yield, which again can result in less PFP.

C4. CONNECTIONS

Bolted connections, e.g. flanges, valve connections, etc., must be verified with respect to need for fire protection. The bolts will normally not obtain any cooling from the fluid inside the pipes.

All bolted connections are pre-tensioned. As the bolts are made of high-strength steel, they usually loose their pre-tensioning, and get softened at a temperature lower than the pipe rupture temperature. This may possibly lead to a leakage even if the stress capacity is sufficient. The acceptability of this leakage must be considered according to the criteria for unacceptable ruptures, ref. Chapter 4.7 of this Guideline.

Normally the temperature in the bolts must be kept below 500 ^{o}C to avoid loosing pre-tension. The factors mentioned above mean that connections often need PFP even where the pipes themselves do not.

C5. SUPPORTS

The pipe/vessel supports and the secondary steel supporting these supports, must keep their integrity until it is acceptable for the pipe/vessel they support to rupture. For this reasons the supports have to be protected by use of PFP unless total integrity can be documented by analyses.

If for any reason it is decided not to use PFP on all the pipe supports, it must be documented by calculations that the change in axial stress due to potential failure of these supports, will not give an unacceptable contribution to pipe rupture.

The secondary steel is not part of the process equipment, and therefore it can be assumed that the integrity of these structures is kept during the investigated fire scenario, as it will be verified for fire as part of the structure analysis.

C6. REFERENCES

/C-1/ Salater and Overå: "Pipes exposed to medium sized Jet Fires - Rupture Conditions and Models for predicting Time to Rupture", FABIG Newsletter, February 2004.