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Petroleum and natural gas industries — Pipeline transportation systems — Reliability-based limit state methods

Industries du pétrole et du gaz naturel — Systèmes de transport par conduites — Méthodes aux états-limites basées sur la fiabilité

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 16708 was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 2, *Pipeline transportation systems*.

Introduction

The International Standard ISO 13623 allows the use of innovative techniques and procedures such as reliability-based limit state methods providing the minimum requirements of ISO 13623 are satisfied.

This International Standard provides the supplement to ISO 13623 in giving recommendations and specifying the framework and principles for the application of the probabilistic approach, i.e. “reliability-based limit state methods”.

Pipeline integrity management during design and operation are performed by the following two limit state approaches:

- a deterministic approach, with the use of safety or usage factors applied to characteristic loads and resistances; and
- a probabilistic approach, based on structural reliability analysis applied to the relevant limit states, e.g. reliability-based limit state methods.

Both approaches satisfy the safety requirements; implicitly by the deterministic approach (via earlier-calibrated safety factors) and explicitly by the probabilistic approach (a direct check on the actual safety level) as illustrated in Figure 1.

Significant differences exist among member countries in the areas of public safety and protection of the environment. Within the safety framework of this International Standard, such differences are allowed for and individual member countries can apply their national requirements for public safety and the protection of the environment to the use of this International Standard.

INTERNATIONAL STANDARD **ISO 16708:2006(E)**

Petroleum and natural gas industries — Pipeline transportation systems — Reliability-based limit state methods

1 Scope

This International Standard specifies the functional requirements and principles for design, operation and re-qualification of pipelines in the petroleum and natural gas industries using reliability-based limit state methods as permitted by ISO 13623. Reliability-based limit state methods provide a systematic way to predict pipeline safety in design and operation.

This International Standard supplements ISO 13623 and can be used in cases where ISO 13623 does not provide specific guidance and where limit states methods can be applied, such as, but not limited to,

- qualification of new concepts, e.g. when new technology is applied or for design scenarios where industry experience is limited,
- re-qualification of the pipeline due to a changed design basis, such as service-life extension, which can include reduced uncertainties due to improved integrity monitoring and operational experience,
- collapse under external pressure in deep water,
- extreme loads, such as seismic loads (e.g. at a fault crossing), ice loads (e.g. by impact from ice keels),
- situations where strain-based criteria can be appropriate.

This document applies to rigid metallic pipelines on-land and offshore used in the petroleum and natural gas industries.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13623:2000, *Petroleum and natural gas industries — Pipeline transportation systems*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
basic variable
load or resistance variable entering the limit state function including the variable accounting for model uncertainty in the limit state function itself

3.2
characteristic load
nominal value of a load to be used in determination of load effects

NOTE Characteristic load is normally based upon a defined fractile in the upper end of the distribution function of the load.

3.3
characteristic resistance
nominal value of a strength parameter to be used in determination of capacities

NOTE Characteristic resistance is normally based on a defined fractile in the lower end of the distribution function of the resistance.

3.4
characteristic value
nominal value to characterize the magnitude of a stochastic variable

NOTE Characteristic value is normally defined as a fractile of the probability distribution of the variable.

3.5
commissioning
activities associated with the initial filling of a pipeline with the fluid to be transported

[ISO 13623]

3.6
construction
phase comprising installation, pressure testing and commissioning

3.7
design life
period of time selected for the purpose of verifying that a replaceable or permanent component is suitable for the anticipated period of service

[ISO 13623]

3.8
design point
most probable outcome of the basic variables when failure occurs

NOTE The design point is the point on the limit-state surface with the highest probability density.

3.9
design value
value to be used in the deterministic design procedure, i.e., characteristic value multiplied by the safety factor

3.10
failure
loss of ability of a component or a system to perform its required function

3.11
fluid category
categorization of the transported fluid according to hazard potential

3.12
importance factor
dimensionless number between zero and one describing the contribution of a random variable to the overall uncertainty

3.13
inspection
processes for determining the status of items of the pipeline system or installation and comparing it with the applicable requirements

EXAMPLE Inspection can be by measuring, examination, testing, gauging or other methods.

3.14
limit state
state beyond which the pipeline no longer satisfies the design requirements

NOTE Categories of limit states for pipelines include serviceability limit state (SLS) and ultimate limit state (ULS).

3.15
limit-state design
structural design where specific limit states relevant for the actual case are explicitly addressed

NOTE A limit-state design check can be made both using the deterministic approach or using the probabilistic approach where uncertainties are modelled.

3.16
limit state function
function of the basic variables, which has negative values when the structure fails and positive values when the structure is safe

3.17
load
any action causing deformation, displacement, motion, etc. of the pipeline

3.18
load combination
set of loads acting simultaneously

3.19
load effect
effect of a single load or load combination on the pipeline

EXAMPLE Load effects include stress, strain, deformation, displacement.

3.20
location class
geographic area classified according to criteria based on population density and human activity

[ISO 13623]

3.21
maintenance
all activities designed to retain the pipeline in a state in which it can perform its required functions

[ISO 13623]

NOTE These activities include inspections, surveys, testing, servicing, replacement, remedial works and repairs.

3.22
maximum allowable incidental pressure
MAIP
maximum allowable internal pressure due to incidental operation of the pipeline or pipeline section

3.23
maximum allowable operating pressure
MAOP
maximum allowable pressure at which a pipeline, or parts thereof, is allowed to be operated

[ISO 13623]

3.24
mean value
first order statistical moment of the probability distribution function of the considered variable

3.25
mill test pressure
test pressure applied to pipe joints and pipe components upon completion of manufacture and fabrication at the mill

3.26
model uncertainty
uncertainty in the predictions of a selected calculation model that remains when the exact values of all input parameters are known

EXAMPLES Load model, strength model, function model for the pipeline.

3.27
nominal wall thickness
specified wall thickness of a pipe, which is equal to the minimum design wall thickness plus the negative manufacturing tolerance and the corrosion allowance

3.28
normal operation
conditions that arise from the intended use and application of the pipeline, including associated condition and integrity monitoring, maintenance and repair

NOTE Normal operations includes steady flow conditions over the full range of design flow rates, as well as possible packing and shut-in conditions.

3.29
ovality
deviation of the pipeline perimeter from a circle, having the form of an elliptical cross-section

3.30
pipeline
those facilities through which fluids are conveyed, including pipe, pig traps, components and appurtenances, up to and including the isolating valves

[ISO 13623]

3.31
offshore pipeline
pipeline laid in maritime waters and estuaries seaward of the ordinary high water mark

[ISO 13623]

3.32
on-land pipeline
pipeline laid on or in land, including lines laid under inland water courses

[ISO 13623]

3.33
reliability
ability of a component or a system to perform its required function without failure during a specified time interval

NOTE Reliability equals 1 minus the failure rate, P_f.

3.34

risk

combination of the probability of an event and the consequences of the event

[ISO 17776]

NOTE Individual risk is related to the risk of a single person injury/death and societal risk is the risk of human safety in the entire society affected by the pipeline.

3.35

safety class

concept to classify the criticality of pipelines

3.36

safety factor

γ

factor by which the characteristic value of a variable is multiplied to give the design value

3.37

specified minimum tensile strength

SMTS

minimum ultimate tensile strength required by the specification or standard under which the material is purchased

3.38

specified minimum yield strength

SMYS

minimum yield strength required by the specification or standard under which the material is purchased

[ISO 13623]

3.39

system reliability

reliability of a system of more than one element, or the reliability of an element which has more than one relevant failure mode

3.40

target safety level

maximum acceptable failure probability level for a particular pipeline and limit state condition

4 Symbols and abbreviated terms

4.1 Symbols

C_f	consequences of a given failure
P_f	probability of a failure, i.e. the actual failure rate calculated
$P_\mathrm{f,\ target}$	target safety level, equal to the target probability of failure
R	resistance or the capability of a structure or part of a structure to resist load effects
S	load effect on a structure or part of a structure
γ	safety factor
$g(x)$	limit state function

D	pipe diameter
L	gouge length of impacts
d	gouge depth of impacts
d_d	dent depth of impacts
f_imp	frequency of occurrence of impacts
f	ovality
σ_y	yield strength
σ_u	ultimate tensile strength
t	time
$f_x(x)$	joint distribution
$I(x)$	indicator function
$H(x)$	event margin
C	vector of serviceability constraints
ΔK	stress intensity factor range
p	random pressure variable
λ	scale parameter
S_C	characteristic load effect
$S_\mathrm{C,E}$	environmental load effects
$S_\mathrm{C,F}$	functional load effects
R_C	characteristic value of component resistance, based on characteristic values of material properties
f_C	characteristic values of material properties, for example yield strength
γ_i	partial load effect factors
η_R	resistance or strength usage factors
γ_m	partial material factors
$\Delta \alpha$	additive partial geometrical quantities

4.2 Abbreviated terms

ALS	accidental limit state
CTOD	crack tip opening displacement
FLS	fatigue limit state
LRFD	load and resistance factor design

MAIP	maximum allowable incidental pressure
MAOP	maximum allowable operating pressure
QRA	quantitative risk analysis
SLS	serviceability limit state
SMTS	specified minimum tensile strength
SMYS	specified minimum yield strength
SRA	structural reliability analysis
ULS	ultimate limit state

5 Principles for design and operation

Pipeline design and operational principles can be implemented using different methods with varying levels of detail as indicated in Figure 1. In order of decreasing level of detail, these methods are quantitative risk analysis (QRA) and structural-reliability analysis (SRA), both of which are probabilistic, and the deterministic limit-state design methods [partial safety-factor design and load and resistance-factor design (LRFD)], which are collectively termed LRFD in this document.

The LRFD formats apply partial safety factors to the characteristic load and resistance properties, representing more traditional design for pipelines. This is the format applied in ISO 13623 by the use of the hoop stress design factor and the equivalent stress design factor, i.e. one partial factor only. This approach is classified as deterministic, as no quantitative information about the safety margin is given. The partial safety factors in the LRFD format have to be calibrated by the use of reliability-based methods prior to the publication to satisfy its design requirements and provide a satisfactory safety margin. The routine use of the LRFD formats do not, therefore, require the partial safety factors to be determined. In LRFD approaches (see left side of Figure 1), the load and resistance are defined by their characteristic values and partial safety factors are applied separately (as required) to the characteristic values of load, resistance and material properties.

Application of the probabilistic approach (SRA and QRA) involves the steps on the right hand side of Figure 1. The limit-state definition is generally the same as for the LRFD. In this approach, load effects and resistance are represented by probability functions, given in terms of distribution type, mean value and standard deviation. This approach is classified as probabilistic, as quantitative information about the safety margin in terms of reliability or the complementary failure probability is given. The most comprehensive probabilistic method is QRA, as it takes into consideration the consequences of failure.

The format and requirements for the reliability-based limit state method are described in Clause 6.

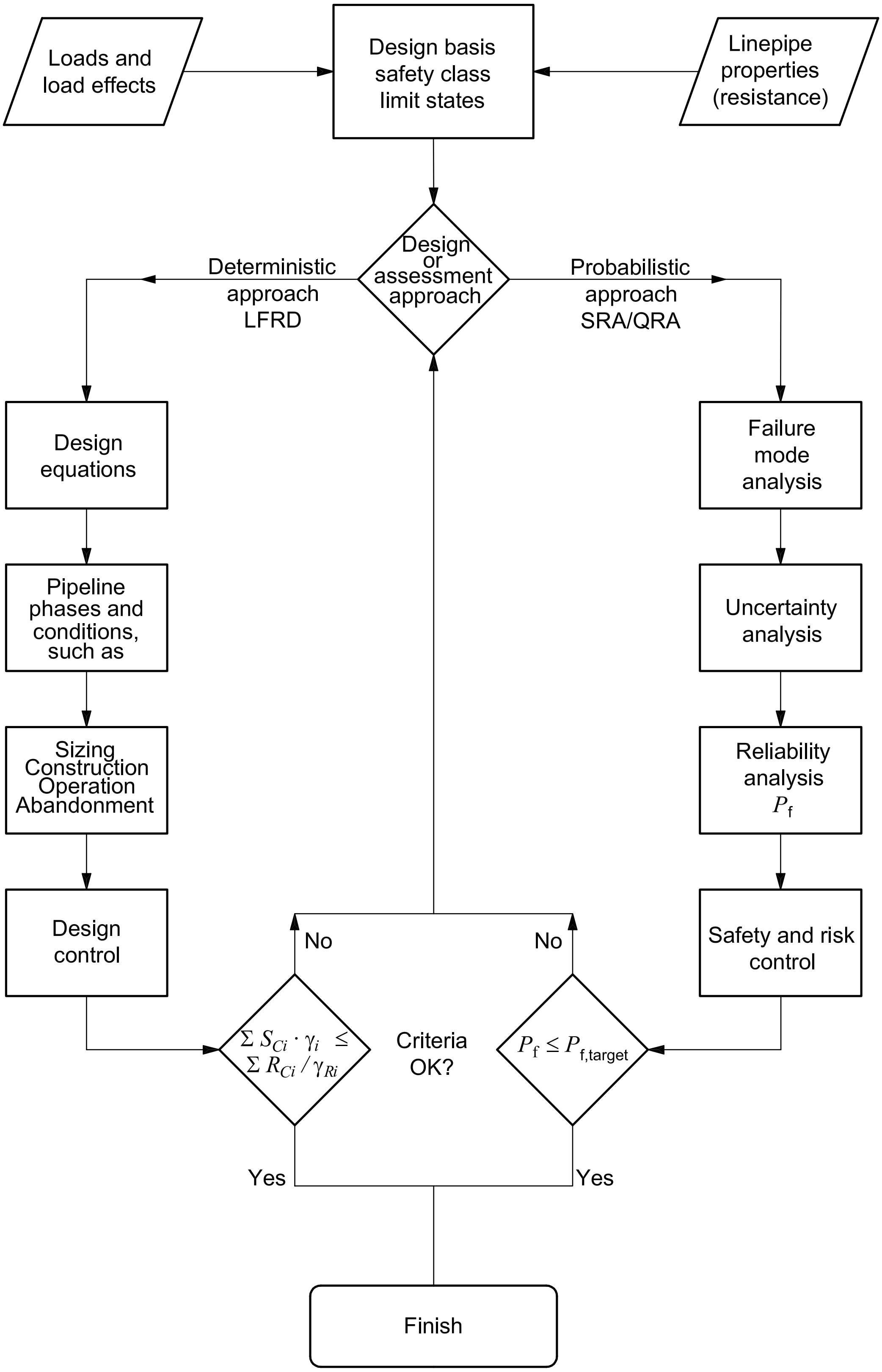


Figure 1 — Pipeline design and assessment approaches

6 Reliability-based limit state methods

6.1 General

Use of the reliability-based limit state approach shall include

- determining the design and operational data basis: data gathering, see 6.2,
- determining the safety requirements: targets, see 6.3,
- failure mode analysis; see 6.4,
- uncertainty analysis including estimation of probability functions; see 6.5,
- reliability analysis, see 6.6, and
- safety and risk assessment, see 6.7.

6.2 Design and operational data basis — Data gathering

Data gathering is collecting and defining all relevant information related to the pipeline to be considered and shall include the following information:

a) design basis and operational information including

  - pipe system characteristics, e.g. pipe diameter, pipeline length, product composition, operating conditions (pressure, temperature), design life and interface facilities,
  - definition of loads and load effects and associated hazards,
  - definition of linepipe properties (resistance) and relevant pipeline capacities, and
  - inspection and monitoring philosophy for operation, e.g. integrity management plan;

b) Hazard identification and classification of failure conditions including

  - determination of limit state conditions which constitute structural non-compliance for the pipeline as judged against the safety requirements and constraints, e.g. partial or total loss of supply, any loss of fluid, loss of operability or serviceability without loss of fluid, and
  - determination how the pipeline can become structurally non-compliant, in terms of loadings, resistance, and degradation; i.e. hazard identification.

Determination of operational requirements and classification of failure conditions shall be performed in accordance with Clauses 7 and 8.

6.3 Safety requirements — target

The objective of this step is to define the relevant safety requirements for the hazards/failure modes.

a) The target safety level shall be defined for all pipeline sections according to the location and consequence categorization in Clause 8;

b) Target safety levels shall be determined for all phases of the pipeline design life; e.g. construction, normal operation, and any temporary conditions.

Target safety levels shall be based upon public safety, environmental and business issues, taking account of safety and serviceability principles dictated by society, the local regulator, the specific company involved, and the performance requirements for the pipeline under consideration.

These targets should be clearly communicated to all relevant stakeholders.

Target safety levels shall be defined in accordance with Clauses 8 and 9. If no risk and/or safety levels are predefined, equivalent target probabilities of failure, $P_{\mathrm{f,target}}$, may be taken from Annex C based on the current state of technology and design practice.

6.4 Failure mode analysis

The objective of this step is to identify all relevant failure modes (i.e. significant hazards with a probability of occurrence larger than the target safety level for the appropriate condition). The steps involved are

a) the gathering of data to assess the severity of all hazards identified,

b) the assessment of each hazard against the target safety requirement to determine whether each hazard is possible but incredible (e.g. a plane crash on a particular pipeline), or both possible and credible (e.g. corrosion),

This analysis may be undertaken in a semi-qualitative manner, e.g. a return period of a particular hazard estimated as being below 10^{-5} /km/year, being smaller than the target performance requirement, implies that the hazard is insignificant, and therefore a probabilistic assessment is not necessary and the hazard can be excluded from the further analysis.

Failure conditions shall be considered according to the classification given in 8.2. Justification shall be given for the classification of any hazard determined to be as “possible but incredible”, such documentation can, for example, be frequencies of occurrence. The significant (possible and credible) failure conditions shall be included in the uncertainty and reliability analysis.

6.5 Uncertainty analysis

In the uncertainty analysis, the significant failure conditions shall be considered, including

a) establishment of all measures that are (or can be) implemented to mitigate against the hazard,

b) determination of the appropriate method of assessment and identification of the most relevant limit state function, e.g. rupture, leak, etc.,

c) collection of data that is required to quantify the variables in the limit state function,

d) assessment of the uncertainty associated with the data and limit state function (model uncertainty), and

e) selection of appropriate values for all variable parameters.

Uncertainty analysis and probabilistic modelling can be performed according to procedures given in Annex A and, if no other case-specific information is available, uncertainty measures can be found in Annex B. The uncertainty modelling should include all variables entering the limit state equation. The most relevant statistical properties are the mean value and the standard deviation in addition to information about the distribution function. Any correlation between parameters is important and shall be evaluated.

EXAMPLE For external corrosion of the pipeline, the mitigation measures can be a combination of any of the following: corrosion allowance, anti-corrosion coating, cathodic protection system, inspection and repair policy. It is noted that there are several ways of implementing an inspection, monitoring and repair policy.

6.6 Reliability analysis

The reliability analysis is to calculate the failure probability (P_f) for each significant limit state identified. The steps to be included are as follows.

a) Probabilistic modelling of the limit state function, i.e. analytical formulation of the failure criteria. For a given limit state, a probabilistic design models the load, S, and resistance, R. The corresponding limit state function may be expressed in the form:

$$g(x) = R - S \tag{1}$$

b) Selection of the most appropriate probabilistic calculation method for the problem and level of accuracy, possible methods include first order second moment (FOSM), “reliability” methods (FORM/SORM), Monte Carlo, or direct integration.

c) Perform probabilistic calculations, i.e. calculate the failure probability for each relevant limit state. The reliability analysis may then be performed when the statistical properties of the limit state functions are defined (load effect and resistance properties). When the distribution functions for R and S are established through uncertainty analysis, the failure probability is calculated by

$$P_\mathrm{f} = \int_{g(x) \leqslant 0} f_{R,S}(R,S)\,\mathrm{d}R\mathrm{d}S \tag{2}$$

The reliability analysis can be performed in accordance with the guidance given in Annex A or other relevant calculation procedures.

A calculated probability of failure is not a physical property of the pipeline itself, but gives a notional value. The calculated probability of failure depends on the method and procedure applied, including uncertainties in data and methods. It is, however, the intent of this document to standardize the methods and procedures used for the reliability-based approach and thus to bring this into a comparable level within the industry.

6.7 Safety and risk assessment

This step is to check that the pipeline meets the safety requirements (criteria). The reliability shall be compared with the requirements by ensuring that:

$$P_\mathrm{f} \leqslant P_\mathrm{f,target} \tag{3}$$

where

P_f is the calculated probability of failure from the reliability analysis;

$P_\mathrm{f,target}$ is the target safety level that should not be exceeded for a design and/or operation to be accepted.

If the requirements are not met, the pipeline details should be modified and the assessment repeated (new iteration in Figure 1).

When applying Equation (3), the correct comparisons shall be undertaken; i.e. individual or system failure modes; for the correct time and spatial units; for the correct phase in the design life, e.g. operational or temporary.

The physical design parameters (e.g. wall thickness) selected to mitigate against failure shall satisfy all performance requirements.

The safety check shall be performed in accordance with Clauses 8 and 9.

Similar safety principles apply to both offshore and on-land pipelines, but differences in failure consequences and safety regimes result in different required target safety levels, $P_\mathrm{f,target}$.

For both offshore and on-land pipeline applications, it is appropriate to control the failure probability (P_f) as a function of the consequences, as established by the safety class designation (see Clause 8) to obtain a uniform risk level. For on-land pipelines, the acceptable probability of failure is also a function of the pipeline pressure and diameter to account for the impact of these parameters on the failure consequences. A uniform risk level is generally the objective for any application.

Equation (3) is equivalent to Equation (4) when risk is calculated as the product of probability of failure and consequences of that failure:

$$\text{calculated risk} \leqslant \text{allowable risk} \tag{4}$$

The target safety levels, $P_{f,\text{target}}$, given in Annex C have been derived from risk assessments and these values may be applied if no additional explicit risk assessment is performed.

Further technical details and requirements of the various items to be considered in the reliability-based approach are described in Clauses 7 to 10 and in Annex A.

7 Design and operational requirements

7.1 General

The safety against potential failure modes shall be checked for all conditions during construction and operation (including re-qualification) throughout the lifetime of the pipeline.

7.2 Design and construction

The pipeline shall be designed and constructed to satisfy the following performance requirements:

a) to perform adequately under all anticipated load effects (serviceability limit state requirement);

b) to withstand anticipated load effects during its construction and operation (ultimate limit state requirements);

c) to avoid failure under repeated load effects during construction and operation (ultimate limit state — fatigue requirements);

d) to avoid failure due to accidents during construction and operation (ultimate limit state — accidental requirements).

7.3 Operation and maintenance

The pipeline shall be operated and maintained such that the safety and the integrity is kept within the target safety level.

An integrity management programme shall be implemented by the operator to satisfy the safety requirements given in this document. Maintenance includes the requirements of inspections, inspections on special occasions (e.g., after an accident or severe environmental events), the upgrading of protection systems and repair of components.

The integrity of the pipeline may be achieved by either a maintenance programme and/or designing to avoid deterioration that can affect the integrity of the pipeline in those areas where the pipeline cannot or is not maintained.

The rate of deterioration may be estimated based on numerical calculations, experimental investigations, experiences from other pipelines or a combination of these.

7.4 Re-qualification

Re-qualification of the pipeline integrity shall be performed when

- the design life is to be extended,
- the pipeline has been found to have deteriorated or have been seriously damaged,
- the pipeline needs to be up-rated,
- the operational conditions change,
- the original design criteria or design basis are no longer valid.

A revised safety assessment in accordance with this document shall be conducted for those aspects of the design not in compliance with the original design requirements.

The re-qualification can require a deviation from the design basis or modifications to the pipeline or the operational conditions to achieve compliance with this document.

7.5 Hazards

Hazards that alone or in combination with loads in normal operation could violate the pipeline integrity shall be considered as part of the ultimate limit state — accidental condition ALS.

a) Possible hazards to the pipeline include

- effects due to extreme environmental loads,
- impact from third-party activities, and
- operational malfunction.

b) Measures taken to mitigate such hazards include

- avoiding the structural effects of the hazards by either eliminating the source or by bypassing and overcoming them,
- minimizing the consequences, and
- designing for hazards.

8 Acceptance criteria and safety classes

8.1 Safety requirements

A target safety level, $P_{\text{f,target}}$ shall be defined as the maximum acceptable failure probability level for a particular pipeline. Target safety levels are required for developing design criteria for the application of reliability methods. These criteria shall be satisfied during operation and maintained through the integrity management programme.

The evaluation of the target safety levels for pipelines should primarily be based on the inherent safety level achieved by using a currently accepted design practice (e.g. code of practice or standard), using uncertainty measures representative of the time when the relevant design practice was prepared. The nature of a failure and the consequence potential in terms of effect on human health and safety, damage to the environment, economic losses, and the cost and effort required to reduce such hazard potential should be taken into account.

The target safety level shall be determined from consideration of

- the type of limit state, see 8.2,
- the fluids being transported, see 8.3,
- the location of the pipeline and potential consequences, see 8.4.

The fluid categorization, location and potential consequences are combined into a safety class, see 8.5. The risk related to the pipeline operation is defined as

$$\text{risk} = \text{probability of failure } (P_\text{f}) \times \text{consequence of failure } (C_\text{f}) \qquad (5)$$

The target safety level can be varied with the consequence of failure to provide a relatively constant risk level; see Clause 9 and Annex C.

NOTE The main objective is to achieve an acceptable reliability for the pipeline from both a safety and economic point of view. It is important to integrate these considerations into the analysis while being in compliance with any requirements from regulators and authorities.

8.2 Classification of limit states

The structural performance of the pipeline shall be described by a set of limit states or failure functions covering the significant failure modes. Each limit state divides the structure performance into two conditions; the safe and the failed condition. Structural design means to satisfy the design requirements for each limit state condition. The following two main categories of limit states shall be considered in the design of pipelines.

- Serviceability limit state (SLS), beyond which the pipeline does not meet its functional requirements, e.g. ovality, ratcheting, accumulated plastic strain, excessive deformations or displacements, damage to or loss of coating.
- Ultimate limit state (ULS), beyond which the pipeline can experience loss of structural integrity, e.g. bursting, rupture, local or global buckling, unstable fracture and plastic collapse. The fatigue limit state (FLS) is a ULS condition covering fatigue due to accumulated cyclic loading and the accidental limit state (ALS) is a ULS condition for extreme load effects for low probability events, e.g. dropped objects, trawl gear hooking, earthquake.

Specification of various load effects to be considered for design and operation of pipelines and the associated limit states are given in Clause 10.

NOTE FLS and ALS are both considered as ultimate failure conditions and belong to the ULS category. However, they are often treated separately to account for the specific failure characteristics. FLS is an accumulated process while ALS is a random instantaneous process. The assessment of ALS takes into account the probability of the accidental event.

8.3 Categorization of fluids

The fluids to be transported shall be placed in one of the following five categories (see Table 1) depending on the hazard potential in respect of public safety (in accordance with ISO 13623).

Table 1 — Categorization of fluids

Fluid category	Description
A	Typically non-flammable water-based fluids
C	Non-flammable fluids that are non-toxic gases at ambient temperature and atmospheric pressure conditions Typical examples are nitrogen, carbon dioxide, argon and air
B	Flammable and/or toxic fluids that are liquids at ambient temperature and at atmospheric pressure conditions Typical examples are oil and petroleum products. Methanol is an example of a flammable and toxic fluid
D	Non-toxic, single-phase natural gas
E	Flammable and/or toxic fluids that are gases at ambient temperature and atmospheric pressure conditions and are conveyed as gases and/or liquids Typical examples are hydrogen, natural gas (not otherwise covered in category D), ethane, ethylene, liquefied petroleum gas (such as propane and butane), natural gas liquids, ammonia, and chlorine

Gases or liquids not specifically included by name should be classified in the category containing fluids most closely similar in hazard potential to those quoted. If the category is not clear, the more hazardous shall be assumed.

8.4 Pipeline location and consequence categorization

The potential consequence of a pipeline failure (C_f) shall be evaluated for the various elements described in Table 2.

Table 2 — Considerations in assessing potential consequences

Element	Considerations
Public safety	Population density and potential for human exposure, potential for ignition and fire, product toxicity
Environmental impact	Land use, product type, production flow rate, volume of release, topography, beach impact, high-consequence areas and ultra-sensitive areas
Business loss	Cost of repair, loss throughput, production loss, impact to remaining life of asset
Corporate reputation	Compilation of all consequence factors, extent of punitive actions by the regulatory agencies and media exposure

The significance of the considerations depend on the pipeline (section) location and are different for offshore and on-land pipelines. Public safety shall generally be given the highest attention, with economical consideration being primarily a matter of concern for the company itself.

Offshore-pipeline consequence evaluation shall consider the proximity to platforms, near-shore or landfall, environmentally sensitive areas and any specific cost considerations, in that order.

For onshore pipelines, consideration shall be given to the population density, pipeline fluids, diameter and pressure, environmental impact and cost. A location categorization (by population density) according to the recommendations in ISO 13623:2000, Annex B, may be applied for on-land pipelines, however, alternative categorizations may be used according to any specific national requirement on public safety.

In determining the level of risk to human safety and environmental damage, i.e. the consequence categorization, account can be taken of the ability to detect a particular loading hazard in time to carry out an emergency response plan that ensures personnel safety and environmental protection.

A typical categorization is proposed in 8.5 with the introduction of safety classes to account for the variability of consequence with location, fluid category, pipeline condition and failure mode.

8.5 Safety classes

Each pipeline shall be classified into one of the four safety classes in Table 3 to account for the consequences of a failure.

Table 3 — Safety classes

Safety class		Description
1	Low	where failure implies insignificant risk of human injury and minor environmental and economic consequences
2	Normal	where failure implies low risk of human injury, minor environmental impact or high economic or political consequences
3	High	where failure implies risk of human injury, significant environmental impact or very high economic or political consequences
4	Very high	where failure implies high risk of human injury

The safety class definition is based on the pipeline location and fluid categories. A safety class shall be assigned to the pipeline as a whole or to sections thereof.

The safety classes given in Tables 4 and 5 may be applied for offshore and on-land pipelines, respectively, unless economic and environmental consequences make a higher safety class more appropriate. An owner can require a higher safety class than that required by Tables 4 or 5.

Table 4 —Minimum safety classes — Offshore pipelines

Pipeline phase	Fluid category [a]	Consequence/location categories		
		Offshore and remote areas	Platform zone	Landfall areas
Construction	NA	Low		
Operating	A, C	Low		
	B	Normal	Normal	Normal
	D, E	Normal	High	High

[a] See Table 1 for definitions of letters.

Table 5 — Minimum safety classes — On-land pipelines

Pipeline phase	Fluid category [a]	Consequence/location categories			
		Negligible	Low	Moderate	High
		Remote area with very low population	Moderate population density	High population density	Very high population density
Construction	NA	Low			
Operating	A, C	Low			
	B	Low	Low	Normal	High
	D, E	Low	Normal	High	Very high

[a] See Table 1 for definitions of letters.

The platform zone and the landfall areas for offshore pipelines shall extend a minimum of 1 km from the outer boundary of the platform and/or the landfall.

For on-land application, a location/consequence categorization in four (4) different levels has been recommended and the safety classified accordingly. Target safety levels related to this number of categorization are given in Annex C where the High and Very High safety classes are selected for situations where the failure consequences are accordingly high. A different categorization may also be applied provided that the general safety framework as given in this International Standard is followed, e.g. a 3-level or a 5-level safety grouping may be used.

9 Target safety levels and risk levels

The application of reliability-based design requires the determination of acceptable safety levels, defined in terms of the target safety levels, $p_{\mathrm{f,target}}$, being the maximum acceptable probability of failure.

Annex C contains guidance on determining the target safety levels and gives values that may be used, when more specific requirements are not available. These values have been derived from calibrations of other codes and standards. The user shall ensure that the values obtained from Annex C are applicable to the specific case.

10 Failure modes

10.1 General

In all the phases of the pipeline lifecycle (design, construction, operation and re-qualification), all load effects and related damage shall be considered, including

- internal pressure load effects,
- external pressure load effects,
- longitudinal load effects,
- damage due to third party activity, and
- combinations of the above.

10.2 Internal pressure induced failure modes

The internal pressure loads are classified into three types:

a) proof pressure (pressure test);

b) incidental pressure;

c) normal operating pressure fluctuations.

The internal pressure primarily induces a tensile hoop stress. The hoop stress due to proof pressure or maximum incidental pressure can result in several overload failure modes, i.e., excessive material yielding, ductile tearing or ultimate rupture/fracture. The hoop stress due to pressure variations can lead to fatigue crack growth.

Hence, the following behaviours shall be identified:

- yielding;
- bursting;
- fracture following crack growth.

Yielding is normally a SLS, as it usually does not result in immediate ultimate failure in fluid containment. Bursting is defined as the point at which the uncontrolled tearing of the pipe wall occurs, which results in ultimate pipe rupture. This is a ULS. For corroded pipes, the burst strength shall be calculated using the reduced wall thickness.

Fracture herein refers to unstable fracture and/or plastic collapse of seam-weld defects when subjected to tensile hoop stress. This is a ULS. Possible ductile tearing during pressure testing and fatigue due to fluctuations of operating pressure shall be included in the fracture assessment. Therefore, an integrated fatigue and fracture assessment is generally required.

10.3 External pressure induced failure modes

The external water pressure on offshore pipelines and both external soil loads (including traffic loads due to road and railway crossings) and buoyancy forces on on-land pipelines induce compressive hoop stresses, which can lead to pipeline failure described by

- ovalization of the pipe cross-section,
- collapse of the pipe cross-section, localized buckling, and
- propagation buckling (offshore pipelines only).

Excessive sectional ovalization is a SLS as it may impact pigging operations. Collapse is a ULS. Propagation buckling relevant to offshore pipelines is associated with damage conditions and is thus an ALS.

10.4 Failure due to external load effects

The external loads and load effects include

- thermal effects,
- external and internal pressures,
- bending moments,
- longitudinal axial forces (due to internal/external pressure, restrained thermal expansion and contraction, ground movements and external forces),
- hydrodynamic forces,
- external soil loads,
- buoyancy forces, and
- transverse loads due to soil/ground movements.

These effects induce compressive or tensile stresses (and strains) in the pipe wall. They can cause failure described by the following limit states:

a) buckling under an overall compressive load;

b) fracture of a girth weld under an overall tensile load, in terms of an interaction of unstable fracture or plastic collapse;

c) ovalization of the cross-section under bending;

d) fatigue.

While buckling and fracture belong to ULS, ovalization is a SLS. Failure is associated with maximum load effects or low capacity. The FLS is normally due to cyclic “non-extreme” longitudinal load effects, e.g., in situations when pipelines are in spanning.

10.5 Failure due to third-party activity

Impacts loads are classified into

a) normal impact loads resulting from, e.g. handling, installation and fishing activities (for offshore pipelines), and

b) accidental impact loads resulting from, for offshore pipelines e.g., anchors, dropped objects and vessels, and for on-land pipelines, e.g. impact from excavation machinery, or other third party activities.

The effects of impact loads can result in

- concrete and passive protection damage,
- permanent dent in the steel pipe,
- notch on the steel surface,
- rupture or collapse of the pipe section, and
- puncture of the pipe wall.

Severe coating damage may constitute a SLS. Apart from possible pigging problems (SLS), permanent denting may lead to local stress concentration. Modes associated with notch, rupture and collapse belong to ULS or ALS, depending upon the frequency of occurrence of the associated impact scenarios.

10.6 Corrosive environment induced failure modes

Corrosive transported fluids (sour oil, sour gas, ammonia, etc.) or external environments (soils, sea water, etc.) can induce different types of corrosion phenomena on pipelines (general corrosion, pitting corrosion, etc.).

Corrosion phenomena which cause metal loss can induce

a) loss of containment,

b) mechanical failure due to pipe wall thinning.

Combination of corrosive environment and stress, both constant and variable, can induce nucleation and propagation of cracks due to

- stress corrosion cracking (SCC),
- corrosion or stress corrosion fatigue.

The incident of SCC requires the concurrence of a susceptible alloy to be exposed to a specific environment at stresses above some limit values. Since SCC only appears in clusters containing numerous individual cracks with sufficient length, this is not a general phenomenon and may be considered as an ALS on a case-by-case basis.

General or pitting corrosion can nucleate fatigue phenomena.

10.7 Failure due to combined loads

In general, pipelines are subjected to simultaneous load actions. A load combination can result in an interaction of failure modes that are associated with individual load effects, or additional failure modes. Load combinations can lead to the following critical limit states:

- collapse under external pressure and impact loads (due to damage);
- rupture under internal pressure and impact loads (due to damage);

- interaction of buckling and collapse under external pressure, bending and axial loads;
- buckling under internal pressure, bending and axial loads.

Each of the above limit states may also be relevant when only one of the loads is present, as discussed in the above. However, the effect of load combination makes the relevant limit state more critical than it would be when any of the single loads acts alone. Therefore, these load combinations usually govern the local design checks.

11 Pipeline operational management

11.1 General

In Clause 11 are addressed the operational requirements to be covered in a pipeline integrity management system being designed in accordance with reliability-based limit state methods.

The pipeline reliability is sensitive to the assumptions made during the design and it is therefore important to ensure these are not violated during the operation of the pipeline.

Adequate monitoring, testing, inspection and audit procedures shall be specified to ensure that the required tolerance limits i.e. limit states, are not exceeded.

The pipeline integrity management system shall include

- management structure, roles and responsibilities,
- operational procedures,
- document control and records,
- integrity aspects and monitoring, and
- pipeline safety, health and environmental aspects.

11.2 Operational management procedures

An important component of the integrity management and monitoring is performance measurement. Analysis of a continuous record of the integrity status of the pipeline allows an understanding of the changing vulnerability of the pipeline to each of the failure mechanisms (limit states) identified during design and allows adequate mitigating actions to be undertaken to prevent failure.

The major operational parameters shall be kept within the specified design limits for all relevant limit states during the operation of the pipeline. Operational and integrity management with inspection and monitoring of critical pipeline parameters and properties is required where the variability in the loads and resistances over the life cycle are otherwise in conflict with the limit states' criteria. The monitoring programme should include the relevant items of the following:

- monitoring operational data, such as pressure, temperature, product composition and condition, flow rate, and, number of shut-downs and/or trips, or composition of well products to ensure that the design premises is not exceeded;
- corrosion monitoring, external and/or internal (e.g. by intelligent pigging);
- monitoring of fluid physical parameters and sampling of the fluid for chemical analysis of corrosive components, corrosion retarding additives or corrosion products;
- weight-loss coupons or other retrievable probes for periodic or on-line monitoring of corrosion rates;

- *in situ* wall measurements by temporary or permanently installed equipment at appropriate locations in the pipeline;
- monitoring of cathodic protection parameters;
- monitoring of landslide movements;
- visual inspection, e.g. to locate dents, or monitor marine growth;
- out-of-straightness surveys, e.g. by geopig to check for out-of-straightness due to frost heave, or soil movements;
- platform riser displacements (on offshore pipelines) monitored by accelerometers, or riser strains monitored using fibre optics.

A pipeline integrity management system defines monitoring and inspection requirements, and actions to be taken as a function the inspection results, such as maintenance activities, repairs, shut down, or revised frequencies of inspection and monitoring.

Advanced numerical calculation and modelling/monitoring (direct assessment) may be applied as a supplement and/or alternative to other inspection procedures, e.g. intelligent pigging, in order to assess the technical integrity of the pipeline during operation.

In general, both the reliability of the pipeline and the consequences of failure depend on the operational management and monitoring efforts. Therefore, any assumptions with regard to operational management, monitoring and conditions that trigger remedial actions (such as derating, shut-down, and/or repair) shall be clearly documented.

The integrity management system shall be reviewed and updated regularly to take account of any degradation or other changes in the pipeline. However, if the operating conditions are changed relative to the design premises, or the key design parameters have reached the limit of their tolerances due to degradation or the effects of external influences, then a re-qualification of the pipeline shall be carried out.

The re-qualification should employ the original limit states, updated as appropriate to reflect accepted current practice, and any new limit states that may be introduced by the influence of the changes.

Re-qualification of the pipeline integrity shall be undertaken when

- the initial design life is exceeded or needs to be extended, e.g. service life extension;
- the pipeline has deteriorated or been seriously damaged, e.g. corrosion/erosion and weld defects, dents, damage to corrosion protection (anodes, corrosion coating) and accumulated fatigue damage due to spanning or instability, etc;
- the operational conditions have been changed or the pipeline needs to be up-rated, e.g. pressure, temperature, corrosivity, etc.; or
- the original design criteria or design basis are no longer valid, e.g. change of the premises as; environmental loads, deformations, scour etc.

The inspection shall be carried out to ensure that the design requirements remain satisfied, no damage has taken place and to monitor any changes in the condition of the pipeline. Key parameters or the influencing phenomena that were identified in the design but are not routinely monitored by the operating control system should be inspected to ensure that they remain within the assumed tolerances. The inspection programme shall address as a minimum the following:

a) exposure of and/or burial depth of buried or covered lines if required by design, regulation or other specific requirements;

b) free-span characteristics;

c) condition of artificial supports to limit free spans installed during construction or as remedial works;

d) local seabed scour;

e) sediment or sand wave movements affecting pipeline integrity;

f) excessive pipe movements including expansion effects;

g) location and characteristics of upheaval or lateral buckling;

h) integrity of flanges and mechanical connections;

i) integrity of subsea valves and protection structures;

j) Y and T connections and protection structures;

k) integrity of pipeline protection structures;

l) performance of external corrosion protection system;

m) internal and external corrosion and erosion;

n) mechanical damage to pipe, coatings and anodes;

o) major debris in close proximity to pipeline;

p) leakage;

q) evidence of anchor or other interference with the pipeline.

Platform risers(on offshore pipelines) shall be included in the long-term inspection programme, with special attention given to the following elements:

- riser displacement due to pipeline movements;
- coating damage;
- extent of marine growth;
- integrity and functionality of supports and guides;
- integrity and functionality of vessel protection structure;
- external corrosion throughout riser and supports;
- internal erosion and corrosion.

The first external inspection should be carried out as soon as practicable after the pipeline has been brought into full operation and within one year of start-up.

A risk assessment should be performed to determine the appropriate frequency of both internal and external inspections throughout the life of the entire pipeline. This should include consideration of the design, fabrication and installation data, degradation mechanisms and failure modes, detection limits and accuracy of the inspection system. The frequency should be reviewed periodically to include the findings of previous inspections, changes in the operating parameters and details of repair and remedial works.

Annex A
(informative)

Uncertainty and reliability analysis — Method description

A.1 General

Analysis of uncertainty is one of the most important and fundamental tasks in structural reliability analysis. Uncertainty is present during the design, construction, commissioning and operating phases of the life of a pipeline; in fact the life of a pipeline itself is also uncertain. In principle, all physical quantities and activities associated with each of these phases are subject to uncertainty and each of them contributes to the structural reliability of the pipeline. However, the degree of uncertainty and the associated impact on the structural reliability of the pipeline depend on the physical quantity or activity under consideration and the amount of available data describing that quantity or activity.

In this annex, a number of physical parameters and activities that can have an impact on the pipeline reliability are identified and discussed. Some guidance is given on their impact on pipeline reliability, on the amount and type of data that are required and on how the data should be collected and analysed. In particular, uncertainties associated with pipeline geometry, material, construction, commissioning, operation and environmental effects and damage are addressed. However, before the specific quantities are addressed in detail the basic nature of uncertainty is described.

Finally, the basic methods and calculation procedures of reliability analysis are described.

A.2 Classification of uncertainties

A.2.1 General

Uncertainties associated with pipeline applications can be divided into two main groups:

a) natural or physical uncertainty;

b) knowledge uncertainty, comprising

  - measurement uncertainty,
  - statistical uncertainty,
  - model uncertainty.

This classification of uncertainty sources is usually adequate. However, transitions between the quoted types can exist. Furthermore, uncertainties related to gross errors are normally not covered within the framework of structural reliability and should be considered by other means.

A.2.2 Natural uncertainty

Natural or physical uncertainty, also known as inherent or intrinsic uncertainty, is a natural randomness of a quantity. It can be sub-divided into two categories:

- uncertainty that can be affected by human factors;
- uncertainty that cannot be affected by human factors.

An example of the first category is the uncertainty related to the strength of steel or a tolerance on a geometric quantity, which can be reduced by use of more advanced production or quality control systems. An example of the second category is the natural variability of an environmental load estimated from a very large representative data set.

A.2.3 Measurement uncertainty

Imperfect instruments and sample disturbance cause measurement uncertainty when observing a quantity. This uncertainty is usually quantified by the manufacturer but can also be evaluated from laboratory or full-scale tests. It can be described in terms of accuracy utilizing its systematic error (bias) and its random error (precision).

If a considered quantity is not obtained directly from the measurements, but some estimation process is interposed, e.g., data processing, a combined model and measurement uncertainty is applied.

A.2.4 Statistical uncertainty

Statistical uncertainty is due to a limited amount of information, such as a limited number of observations, which causes uncertainty in the estimation of statistical parameters.

In situations where few data describing a particular parameter are available, it can be possible to improve the estimate of the uncertainty in that parameter based on additional information and the use of Bayesian statistics. For instance, the uncertainty in yield strength and wall thickness can be improved based on the knowledge of survival of the pressure test.

A.2.5 Model uncertainty

Model uncertainty is uncertainty due to imperfections and idealisations made in the applied physical and probabilistic models, and reflects a general confidence in the applied model to describe “real life”. It can further account for unknown effects of other variables and their interaction, which are not included in the model.

Model uncertainty in a physical model for representation of load or resistance quantities can be represented by a stochastic factor defined as the ratio between the true “real life” quantity and the quantity described by the model. A mean value not equal to 1,0 expresses a bias in the model prediction of reality while the coefficient of variation expresses the corresponding variability of the prediction.

For a capacity formulation, a model uncertainty is usually applied in order to reflect the confidence in the ability of an analytical equation (or finite element model) to describe a real life situation. In order to assess the adequacy and confidence in this approach, a number of evaluations and verifications can be performed e.g. using a finite element approach or laboratory test.

In the case of load or load-effect modelling, model uncertainties can be relevant concerning the choice of distribution, determination of measurement period, distribution fitting procedure applied and unaccounted tail behaviour from extrapolations.

Thus, an adequate assessment of the model uncertainty can be available from sets of laboratory or field measurements, physical reasoning, refined analyses or sound engineering judgement. However, subjective choices of the distribution of a model uncertainty will often be necessary.

A.3 Determination of probability distributions

A.3.1 General

The probability distribution for a random variable represents the uncertainty of the variable. The results of a reliability analysis can be very sensitive to the tail behaviour of the probability distribution applied, so a proper procedure for the choice of distribution is necessary.

The process of establishing a probability distribution for a stochastic variable, referred to as statistical inference, consists of the following steps:

- choice of distribution model;
- estimation of distribution parameters;
- certification of fitted distributions.

A.3.2 Choice of distribution model

The selection of the appropriate mathematical formulation of the probability distribution function for a particular random variable should be based on experience from similar types of problems, physical reasoning or analytical results.

Alternatively, the choice can be made based on the goodness of fit of the distribution to empirical data. This approach is relevant when a significant amount of data is available in which case estimates of the coefficients of skewness and kurtosis can be used to select a class of appropriate models and to exclude inappropriate ones.

Some of the most frequently used distributions relevant to pipeline problems include

a) beta distribution to model distributions of bounded variables;

b) lognormal distribution to model resistance variables where the information is limited;

c) normal distribution to model linear physical parameters and additive independent errors;

d) uniform distribution to model physical phenomena, e.g. directional distributions of current;

e) Weibull distributions to model long-term wave heights and current values. The Weibull distribution contains the well-known exponential and Rayleigh distributions as special cases.

f) Gumbel distribution to model extreme values of variables having parent distributions of the exponential type.

The underlying generation mechanism should be taken into account in order to evaluate whether it can be considered an approximation to a well-known stochastic experiment, e.g.,

- the additive mechanism leads to a normal distribution (central limit theorem);
- the multiplicative mechanism leads to a lognormal distribution;
- extreme values are modelled by type I,II,III asymptotic distributions, i.e. distributions for the smallest or largest values;
- Poisson processes are modelled by Poisson and Gamma distributions.

The extreme by power n distribution is used to model the smallest or largest value in a sample containing n independent and identically distributed variables with the parent distribution $F_x(x)$. The distribution functions for the maximum and minimum values are given by Equations (A.1) and (A.2):

$$F_{\text{max}}(x) = \left[F_x(x)\right]^n \tag{A.1}$$

$$F_{\text{min}}(x) = 1 - \left[1 - F_x(x)\right]^n \tag{A.2}$$

When applying a flexible distribution model with a large number of adjustable parameters (e.g. Hermite or generalized gamma distribution), extreme caution should be exercised if the model is selected on the basis of a limited amount of sample data.

A.3.3 Methods for estimating distribution parameters

A.3.3.1 Graphical procedure

The distribution parameters can be estimated from plots using engineering judgement or a fit-by-eye approach.

A.3.3.2 Least square fit method

The distribution parameters can be calculated through a minimization of $\Sigma(x_{i,\text{obs}} - x_{i,\text{model}})^2$ where $x_{i,\text{obs}}$ is an observed quantity and $x_{i,\text{model}}$ is the corresponding distribution model prediction. This corresponds to a linear or non-linear optimisation problem dependent on the distribution type.

A.3.3.3 Maximum likelihood estimation technique

Estimates of the statistical uncertainty related to the distribution parameters for limited data sets can be obtained using this technique, which yields asymptotically unbiased estimators. The technique is appropriate for large single population samples where the extreme distribution tail behaviour is of secondary importance.

A.3.3.4 Method of moments

The method of moments can be applied to evaluate distribution parameters by assigning analytical moments to the sample moments. Usually estimates for the four moment estimators mean (μ), standard deviation (σ), skewness (δ) and kurtosis (κ) are applied. For a sample containing n measurements, x_1, ..., x_n, these estimators are calculated as follows:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{A.3}$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \mu\right)^2 \tag{A.4}$$

$$\delta = \frac{\dfrac{n}{(n-1)(n-3)}\displaystyle\sum_{i=1}^{n}\left(x_i - \mu\right)^3}{\sigma^3} \tag{A.5}$$

$$\kappa = \frac{\dfrac{n^2 - 2n + 3}{(n-1)(n-3)(n-3)}\displaystyle\sum_{i=1}^{n}\left(x_i - \mu\right)^4}{\sigma^4} + \frac{3(n-1)(2n-3)}{n(n-2)(n-3)} \tag{A.6}$$

A.3.3.5 Bayes estimation

The Bayes estimation technique enables the uncertainty associated with the estimation of the distribution parameters to be updated as more information becomes available by applying Bayes' theorem. The method is recommended where available statistical information is limited and engineering judgement, intuition or experience gives strong indications on the choice of distributions or value of distribution parameters.

A.3.4 Verification of distributions

The final stage in the process of selecting a distribution is model verification. The adequacy of a fitted model can be indicated by objective methods or by subjective judgement. The most commonly adopted objective methods [8] are

- Kolmogorov-Smirnov test;
- χ^2 test (Chi-square test).

These classical statistical methods are used to check whether there is evidence to reject a candidate distribution. Especially when the available data are few, lack of evidence to reject a candidate distribution does not necessarily mean that the distribution is the correct one. Therefore, engineering judgement based on a probability plot is often the preferred approach. Such verification can be performed by plotting both the empirical and the fitted distribution function in a quantile plot or in a plot constructed so that the fitted model appears as a straight line. The verification can then be focused on the important part of the distribution, (left tail, right tail or central part of the distribution).

A.4 Assessment of statistical uncertainty

A.4.1 General

The statistical uncertainty is a function of the type of distribution fitted, the estimation technique, the value of the distribution parameters and the amount of underlying data. The implication of this uncertainty can be assessed using a parametric Bootstrapping simulation technique [1], the maximum likelihood method, linear least square regression or by approximate measures guided by experience.

A.4.2 Parametric simulation technique

The procedure in parametric Bootstrapping simulation technique is as follows.

a) A set of parameter values is determined by fitting to the set of n observations (using one of the techniques described in A.3.3).

b) These parameter values are taken as the true parent parameters, and N samples of n outcomes of the parent distribution are generated.

c) For each sample, new parameter sets are estimated by the fitting method.

d) The statistics of the distribution parameters, e.g. the four lower moments and correlation coefficients, are estimated from the N realisations.

e) The distribution is randomized by assigning distributions to the parameters.

Alternatively, a new distribution (continuous or extreme value distribution), including the statistical uncertainty, can be generated from the N samples using a Monte Carlo approach.

A.4.3 Approximate assessment

For independent distributed samples, the standard deviation of the moment estimators are given as follows:

$$s_\mu = \sigma / \sqrt{n} \tag{A.7}$$

$$s_\sigma = \sigma \sqrt{\frac{\kappa - 1}{4\,n}} \tag{A.8}$$

$$s_\delta = \sqrt{6/n} \tag{A.9}$$

$$s_\kappa = \sqrt{24/n} \tag{A.10}$$

where μ, σ, δ, κ and n are defined above. The first two expressions are valid in general while the latter two expressions are valid for normal samples only but can be taken as approximations in non-normal cases.

A.4.4 Bayesian approach

The Bayesian approach is also based on an assumed form of the distribution function for the random variable under consideration (e.g. normal) involving a number of distribution parameters (e.g. the mean and standard deviation of a normal random variable). However in this case, the probability distribution for the distribution parameters is calculated explicitly, using the available statistical data. These probability distributions are then used in the subsequent analysis to account for statistical uncertainty. The steps involved are as follows.

a) Estimate a prior probability density function for the distribution parameters, based on any information other than the statistical data to be used subsequently. If there is no prior knowledge, then a non-informative prior (for which the probability density is a constant) can be used.

b) Using the Bayesian methodology, obtain the probability distribution for the distribution parameters given the available statistical data. This is referred to as the posterior distribution.

c) By considering all different possible values of the distribution parameters, and their relative likelihood described by the posterior distribution function obtained in Step 2, calculate the predictive distribution for the random variable under consideration.

d) Use the predictive distribution for the random variable under consideration in the subsequent SRA.

A.4.5 Combination of uncertainties

Let $f(x)$ be a function of a set of stochastic variables. If the various components of x are independent, the variance of $f(x)$ can be approximated by

$$\sigma_f^2 = \sum \left[\frac{\delta f\left(X = x_0\right)}{\delta x_i} \right]^2 \sigma_{xi}^2 \tag{A.11}$$

where σ_{xi} is the standard deviation of ith uncertainty source.

If $f(x)$ is close to being linear, this can provide an acceptable measure of the combined uncertainty.

Various components of uncertainty (e.g. physical uncertainty, several sources of measurement uncertainty and statistical uncertainty) can be combined using the above simple formula.

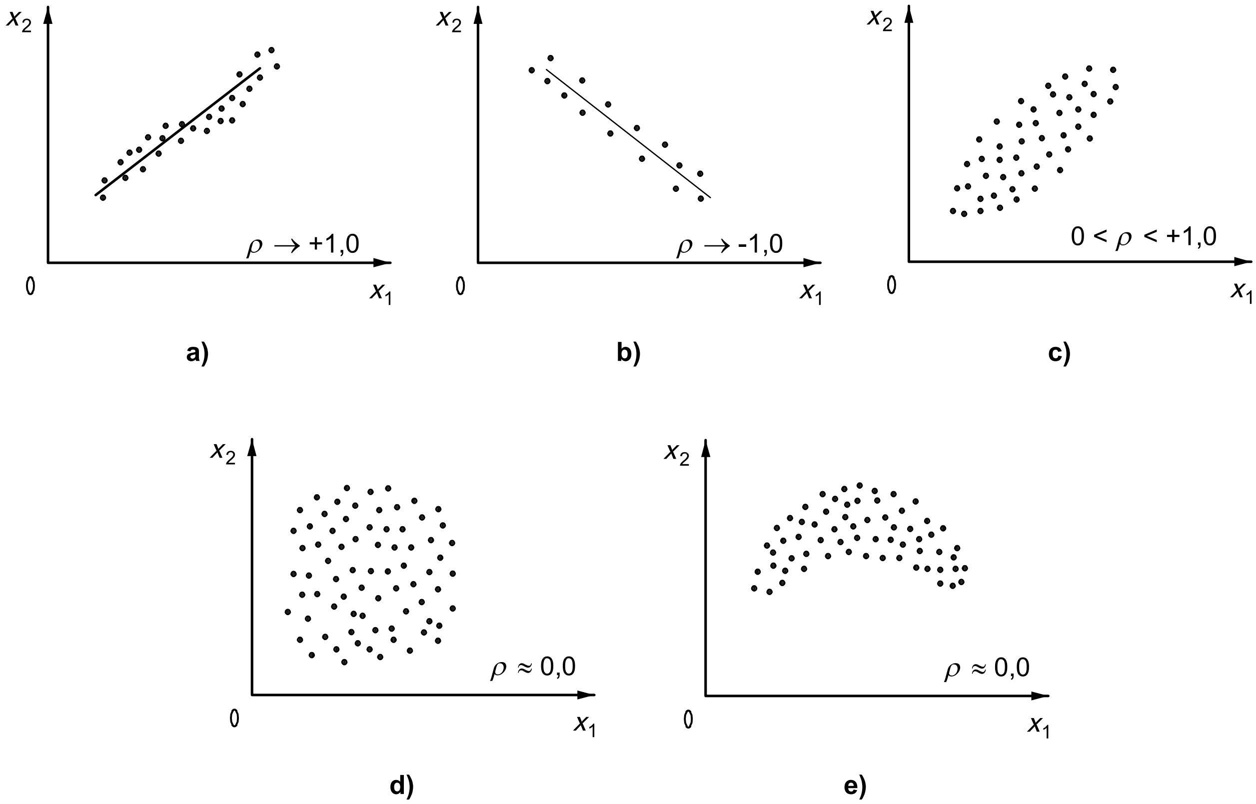
A.5 Joint description of variables

In a reliability analysis, all significant variables should be considered. If the variables are independent, the joint description (i.e. the joint distribution) of the variables is obtained as the product of the marginal distribution. However, in most cases some of the variables involved are mutually dependent. The effect of this, for two dependent variables x and y, can be included in the analysis by introducing a correlation coefficient, ρ, defined as

$$\rho = \frac{\sum_{i=1}^{n} x_i \, y_i - n\mu_x\mu_y}{(n-1)\sigma_x\sigma_y} \tag{A.12}$$

As illustrated in Figure A.1, the correlation coefficient implies the following relationships:

- perfectly positively correlated if $\rho = 1$;
- perfectly negatively correlated if $\rho = -1$;
- positively correlated if $0 < \rho < 1$;
- negatively correlated if $-1 < \rho < 0$;
- uncorrelated if $\rho = 0$.



a) b) c)

d) e)

Figure A.1 — Illustration of the correlation coefficient

In general, the following classification is used:

- strong (high) correlation if $|\rho| \geqslant 0{,}9$;
- moderate (medium) correlation if $0{,}5 \leqslant |\rho| < 0{,}9$;
- weak (low) correlation if $|\rho| < 0{,}5$.

The mutual dependency among the variables can be ignored if

a) the variables are weakly correlated;

b) the dependency is among variables with low importance factors;

c) omission of the dependencies among the variables is conservative.

A.6 Typical uncertainty measures

A.6.1 General

In the probabilistic design of pipelines, uncertainty measures are required for the variables describing

- linepipe properties;
- loads and load effects;
- external third-party interference;
- construction defects;
- corrosion.

A.6.2 Linepipe properties

Linepipe properties, including dimensional and material strength parameters, depend upon type of pipe (e.g., seamless or seam-welded), type of material (e.g., carbon steel or duplex steel) and manufacturing specifications. Such properties are relevant to all limit states and for both offshore and on land pipeline applications. Their uncertainty measures can be obtained by statistical analysis of mill data. In Annex B, the following parameters are covered:

- wall thickness;
- pipe diameter;
- pipe ovality;
- yield strength;
- ultimate tensile strength;
- Charpy V-notch impact energy;
- critical crack tip opening displacement (CTOD);
- S-N curves and fatigue crack growth parameters.

The wall thickness has an effect on most failure modes, including external interference and corrosion. Typically, a nominal value is quoted and, although there is no precise statistical interpretation of this value, it is usually a reasonable approximation of the mean.

The yield strength, σ_y, is nominally characterized by the specified minimum yield strength (SMYS). The yield strength is subject to measurement, statistical and natural uncertainty and the SMYS value typically represents the lower (1 to 5) percentile of the probability density function which describes natural uncertainty. (The precise statistical significance of SMYS is not usually known.)

The probability density functions for wall thickness and yield strength can be constructed from information provided by pipe mill certificates. The probability density function can usually be represented by either normal or lognormal distributions characterized by computed estimates of the mean and standard deviation. Confidence limits on these statistics depend on the amount and variability of the data; more data leads to greater confidence. However, in situations where few data are available, confidence in the distribution of wall thickness can be significantly enhanced using Bayesian statistics to update the distribution based on survival of the hydrostatic test.

The ultimate tensile strength, σ_u, is nominally characterized by the specified minimum tensile strength (SMTS). Limit state functions associated with failure modes of pipelines often account for tensile strength effects by implicitly or explicitly applying a factor (Y/T ratio) to the yield strength.

The material toughness is generally used to determine the resistance to crack initiation (brittle or ductile) and crack propagation.

The resistance to crack initiation is best described by a fracture mechanics toughness property such as the crack tip opening displacement (CTOD).

Resistance to crack propagation or the ability to effect crack stop is commonly described by the results of Charpy V impact tests in combination with drop weight tear (DWT) tests. Minimum requirements for the impact energy are given in References [2] or [30]. The ductile fracture behaviour can be shown by DWT tests as the DWT tests correctly predict the ductile to brittle transition temperature of the linepipe material [3], [4].

A.6.3 Loads and load effects

Pipelines are subject to various types of external loads including loads due to external hydrostatic pressure, ground movement, sea currents, self-weight effects at free spans and trawl lines offshore.

Uncertainties for loads and load effects are case-specific. However, for each category of load and load effect (functional or environmental), a range of load variability for typical scenarios can be found by analytical analysis or numerical simulations.

In Annex B, the following loading properties are covered in relation to offshore pipelines:

- internal pressure;
- functional load effects relevant to installation and for the as-laid pipe;
- environmental load effects relevant to installation and for the as-laid pipe.

A.6.4 External interference

External impact from excavating machines is historically the most frequent cause of failure of pipelines on land. The impact generally results in a dent containing a gouge. Uncertainty exists in the dent depth, d_d, the gouge length, L, the gouge depth, d and the frequency, f_{imp}, of occurrence of impacts. Unless it can be shown that the pipeline under consideration is not, or will not be, susceptible to such impacts it is important to quantify the uncertainties in these four parameters.

For situations involving existing pipelines, databases describing this uncertainty might have been constructed by, or on behalf of, the pipeline operator from inspection records.

When considering the design of new pipelines it may be appropriate to use existing databases if it can be shown that the new pipeline will not be subject to a more onerous environment than the existing ones. In situations where this cannot be demonstrated or where no data is available, appropriate conservative estimates of the uncertainty must be used.

A single deterministic best estimate value of f_{imp} is normally adequate for the structural reliability analysis.

The Weibull distribution is commonly used to describe the uncertainty in the physical dimensions of damage. The suitability of this distribution can be readily determined by visual examination of the linearity of the data on a Weibull plot for each of the quantities, d_{d}, L and d.

A.6.5 Construction defects

Any defects present at the start of life in girth or seam welds can increase in size due to fatigue crack growth. Therefore, unless it is known that the pipeline is not, or will not be, subject to any significant cyclic loading, it is essential that the effect on structural reliability of both seam and girth weld defects is taken into account. In this case, natural, statistical, measurement and modelling (growth law) uncertainties exist. Acceptable defect sizes for linepipe girth welds can be assessed according to, for example, Reference [5].

The type, size and number of defects that can be present at the start of life depend on factors such as the welding technique, the welding parameters, the orientation of the defects, the reliability and accuracy of the weld inspection technique, the hydrostatic test pressure and the strength and toughness of the weld. If inspection records are available, it can be possible to construct distributions describing the uncertainty in defect length, $L(0)$, and defect depth, $d(0)$, at the start of life, directly from these records. This distribution can be improved (statistically updated) based on the further knowledge that the pipeline survived the hydrostatic test.

When inspection records are unavailable (which is commonly the case), one possible approach is to construct distributions of $L(0)$ and $d(0)$ based on survival of the hydrostatic test and the known distributions of weld strength and toughness. In this case, either the distribution of $L(0)$ is assumed and the distribution of $d(0)$ is determined or vice versa.

It is important to note that the distributions obtained are start-of-life distributions. Fatigue-crack growth is a time-dependent process and it is, therefore, important that appropriate time-dependent transformations of these distributions or the failure space (limit-state functions) are invoked.

A.6.6 Corrosion

Various types of corrosion including internal, external and stress corrosion cracking can effect the structural reliability of a pipeline. In order for any type of external corrosion to occur, there must be a breach of the external coating and a breakdown of the cathodic protection system near the breach. The rate of growth of corrosion defects, which can follow the occurrence of these two events, is very dependent on the local environmental conditions and can depend on time. It follows that at any time, t, considerable uncertainty exists in the number of defects present, $n(t)$, and the length, $L(t)$, depth, $d(t)$, and rate of growth, $r(t)$ of each defect.

When inspection records from a number of inspections made over a number of years on the pipeline under consideration are available, it can be possible to construct distributions describing the variation in the size of corrosion defects at given times. The effects, on these distributions, of repairs made in accordance with appropriate criteria can also be taken into account.

When inspection records are not available, data obtained from inspections on similar pipelines can be used. Weibull distributions characterized by time-dependent parameters can be used to model the uncertainties in $L(t)$ and $d(t)$. The number of defects present depends on the rate of occurrence and the repair criteria.

A.7 Reliability analysis

There are two main applications of reliability analysis:

- complete probabilistic design check (SRA), i.e. the probability of failure is explicitly calculated and checked against the acceptance criteria, $P_{\text{f,target}}$;
- calibration of partial design factors to be used together with a selected LRFD format, i.e. to develop the LRFD format and determine the safety factors.

For a given limit state, a probabilistic design involves modelling of the generalised stochastic load, S, and generalized stochastic resistance, R. As a simple illustration, the corresponding limit state function can be expressed in the form of

$$g(x) = R - S \tag{A.13}$$

When the distribution functions for R and S are established through uncertainty analysis, the failure probability is then calculated by

$$P_{\text{f}} = \int_{g(x) \leqslant 0} f_{R,S}(R,S)\,\text{d}R\,\text{d}S \tag{A.14}$$

The probabilistic design check can then performed using the following design format:

$$P_{\text{f,calculated}} \leqslant P_{\text{f,target}} \tag{A.15}$$

where

$P_{\text{f,calculated}}$	is the calculated probability of failure from the reliability analysis;
$P_{\text{f,target}}$	is the target value that should be satisfied for a design to be accepted.

The probabilistic (or reliability-based) design approach involves the following steps:

- identification of all relevant failure modes (i.e. limit states) and limit state equations;
- uncertainty modelling of variables entering the limit state equations;
- determination of the target safety levels (recommendations given herein);
- calculation of the failure probabilities for each limit state.
- comparison against acceptable failure probabilities or calibration of design factors (decision parameters) so that the target probability level is achieved

Guidance concerning the three last steps in this process is given in Annex C. Guidance is also given on how to calibrate partial safety factors in the LRFD format by using the probabilistic calculation procedures.

A.8 Reliability calculation methods

A.8.1 Calculation of failure probabilities

The probability of failure of a pipeline, P_f, is defined by

$$P_\mathrm{f} = \int_{g(x)\leqslant 0} f_x(x)\,\mathrm{d}x \tag{A.16}$$

where

x is a vector of stochastic variables

$f_x(x)$ is the joint probability density function

$g(x)$ is the limit state function where $g(x) \leqslant 0$ signifies failure.

The function, $g(x)$, can represent a single failure cause, i.e., single event function, or a system representation of several failure modes. Only few analytical solutions of the above integral exist, and traditional numerical integration is very time consuming and costly due to the high number of stochastic variables normally occurring in reliability applications. Estimates of the failure probability can be obtained by the following complementary approaches:

- approximate analytical methods;
- Monte Carlo simulations;
- nested reliability methods.

The theory and methods of structural reliability have developed significantly during the last two decades. Intensive research on both philosophical and conceptual issues as well as on computation methods has been performed and the field has now reached a stage where use of the developed methodology is becoming widespread. The methods and application of structural reliability theory have been documented in an increasing number of textbooks e.g. References [6], [7], [8], [9], [10] and [11] along with numerous papers dealing with the subject. A number of analysis tools are at present also available on the open market.

A.8.2 Approximate analytical methods

Approximate analytical methods include the so-called first-order reliability method (FORM) and second-order reliability method (SORM). The basic approach of the analytically based approximate methods is a transformation of the stochastic variables into a probability space of standardized, mutually independent normal variables, and to approximate the probability integral by simplifying the boundary of the integration domain.

These methods have support from asymptotic analysis and are particularly useful for the high-reliability problems often encountered in engineering. A good approximation to the failure probability can often be obtained by replacing the true boundary of the integration domain by the first-order (FORM) or second-order (SORM) Taylor expansions of the failure function about the design point. A requirement for the FORM and SORM analyses is that $g(x)$ is twice continuously differentiable in the vicinity of the design point.

The simplified methods are motivated by the fact that calculation of points on the failure surface in some cases is very costly, e.g., if for each iteration in normalized space a new time-consuming finite element analysis is required. It is, therefore, important to establish methods in which the number of $g(x)$ calculations is kept to a minimum. It should also be mentioned that the number of iterations can in some cases be reduced by application of response surface techniques.

A.8.3 Monte Carlo simulations

The Monte Carlo simulation method samples from the joint distribution $f_x(x)$, and the indicator function $I(x)$, defined as $I(x) = 1$ if $g(x) \leqslant 0$ and $I(x) = 0$ if $g(x) > 0$, is evaluated at each sample point. An unbiased estimator for the failure probability is then given by the sample mean

$$\hat{P}_{\mathrm{f}} = \sum_{i=1}^{N} I(x_i) \tag{A.17}$$

An advantage of the method is that it makes use of point values of $g(x)$ only, and that $g(x)$ and the distributions do not require any analytical properties. The disadvantage is the computational time for small probabilities. Improved efficiency of simulations can be obtained by using the following more advanced simulation (sampling) techniques:

- importance sampling;
- Latin hypercube sampling;
- adaptive sampling;
- conditional simulation methods;
- directional simulation;
- axis-orthogonal simulation.

A.8.4 Nested reliability methods

Nested reliability methods are required when reliability calculations are included in the limit state function, i.e. in case of

- applications involving time-dependent variable conditioned on time-independent variables;
- first passage failure event as out-crossing of a stochastic process through an uncertain failure surfaces;
- determination of the distribution of the failure probability due to subjective uncertainties;
- separation of differentiable and non-differentiable variables. The non differentiable variables (e.g., discrete variables) require analysis by simulation techniques, while a FORM /SORM analysis can be performed for a sub set of the total variable vector.

In time-dependent problems, emphasis is on the study of the probability that a stochastic vector process (e.g. a load process) leaves a safe domain at least once during a time interval [0,T]. In the case of one load only, the maximum extreme load within the time interval can be modelled as a stochastic variable with a given (extreme value) distribution function. For several time-dependent load processes, the extreme value distribution is, in general, unknown, and a useful concept for determination of the first passage failure probability is the mean rate of out crossing of a vector process from the safe region.

The safe domain itself can also be time-dependent, e.g., due to structural deterioration caused by damage such as fatigue, crack growth, creep, corrosion, erosion or wear. The structural failure can be defined as the event of a damage indicator for the first time reaching a critical value.

The first passage failure probability can be approximately given in many cases, e.g. for high thresholds and not too narrow-banded processes, by adopting the Poisson hypothesis of independent failure surface crossings:

$$P_{\mathrm{f}} = E_x\left[P_{\mathrm{f}}(X)\right] \tag{A.18}$$

in which E[ ] is the expectation operation, and

$$P_{\text{f}}(x) \approx 1 - \exp\left[-\int_{0}^{T} v(t,x)\,\text{d}t \right] = 1 - \exp\left[-v(x)T \right] \tag{A.19}$$

where the latter equality is valid for stationary conditions. The conditional mean crossing rate $v(t,x)$ can be calculated as a particular parametric sensitivity factor of a parallel system.

A.8.5 Reliability updating

The reliability assessment of a pipeline in the design phase is based on the available prior information. When assessing the reliability of the pipeline at a later stage, new information that has become available during construction or operation can lead to a better estimation of the structural performance or a reduction of the subjective uncertainties.

Let the new information be formulated through the event margin $H(x) < 0$. Through Bayes' theorem, it follows that an updated failure probability is obtained as

$$P\left[g(x) \leqslant 0 \mid H(x) \leqslant 0 \right] = \frac{P\left[g(x) \leqslant 0 \cap H(x) \leqslant 0 \right]}{P\left[H(x) \leqslant 0 \right]} \tag{A.20}$$

which corresponds to a ratio between a parallel system failure probability and a single event failure probability. An example of $H(x) \leqslant 0$ can be “no bursting during mill test”. A distribution function for a variable, Z, can also be updated by defining $g(x) = z - Z$. Alternatively, more traditional Bayesian updating of distributions using conjugated distributions or simulation techniques can be applied.

A.8.6 System reliability

A pipeline is from a probabilistic point of view a series system, i.e., the pipeline fails if any of its components (sections or joints) fails. It is thus important to establish a relation between the component reliability and the system reliability.

For series systems with equally correlated failure components the probability of failure for the system $P_{\text{f,sys}}$ can be formally written:

$$P_{\text{f,sys}} = 1 - \int_{-\infty}^{\infty} \phi(x) \prod_{i=1}^{n} \Phi\left(\frac{\beta_i - \sqrt{\rho}\,x}{\sqrt{1-\rho}} \right) \text{d}x \tag{A.21}$$

where

n is the number of components in the system;

β_i is the reliability index for failure element I;

ρ is the common correlation coefficient between any pair of safety margins for components i and j, $i \neq j$.

The correlation coefficient can be approximately estimated from the physics in the failure mode, material properties and importance factors obtained from the component reliability analysis. In case of a limited number of failure components, the assumption of selecting an appropriate correlation coefficient might not be crucial and the “equi-correlated system approach” can prove to be feasible.

Alternatively, an extreme value approach can be applied. The basic assumption is that failure for the system can be confined to a single critical component. The definition of such a critical component depends on the physics of the problem and the limit state function considered. For pipelines, a critical component is often location-specific and associated with an extremely low capacity or subjected to an extreme load. Assume that the capacity consists of a function of variables $C = f[Y_1(\lambda), Y_2(\lambda), ..., Y_n(\lambda)]$ where $Y_i(\lambda)$ is a capacity variable (e.g., $Y_1 = t$, Y_2 = SMYS, etc.) and λ is the location. The smallest minimum for the total capacity, C_{min}, can then be estimated using a Turkstra-rule type of combination approach, i.e.

$$C_{\text{min}} = \min\left\{ f\left[Y_1(\lambda), ..., Y_1^*(\lambda), ..., Y_n(\lambda) \right] \right\}_{i=1,...n} \tag{A22}$$

where $Y_i^*(\lambda)$ denotes a maximum or minimum value which leads to the lowest capacity.

If the capacity variables $Y_i(\lambda)$, $i = 1, ..., n$, are statistically dependent, the conditional distribution for the "non-leading" variables $Y_j(\lambda)$ should be used or else $Y_j(\lambda)$ should be taken from the parent distribution.

The extreme value approach ensures that the smallest likely capacity is used in the reliability analysis. If, however, $Y_i(\lambda)$ originates from different sources, all combinations in the above min operation should be evaluated. The above approach is considered equivalent to a generalized Turkstra rule approach for combination of a function of time-dependent loads. It provides reliable estimates if the assumption of independence of variables in different components holds and the random variable chosen to characterize the critical component is dominant. However, the proposed method remains an assumption and the model guided by physical reasoning.

The shortcomings of the "equi-correlated system approach" are the difficulty in estimating an appropriate correlation coefficient while for the extreme value approach the weak point relates to the load combination. For most well understood problems, the two approaches will render equivalent results and the system reliability assessment can be performed using either of the above methods. It is recommended that one method should be selected based on the physics of the problem and verified by the other.

A.9 Interpretation of results

The basic results of a probabilistic analysis are comprised of

- failure probability;
- design point giving the most likely values of the basic variables at failure;
- importance and sensitivity factors.

The main purpose of an evaluation is to examine whether the design point is reasonable based on engineering judgement and experience from similar types of problems and that it is not in conflict with obvious physical knowledge or limitations. First, it has to be checked that the obtained design point from the reliability analysis is a global minimum solution to the optimization problem rather than a local minimum. Further, the results from the reliability analysis also have to be assessed by verifying that the design point corresponds to physically realizable outcomes of the stochastic variables. If a response surface technique is applied, it is necessary to verify that the response surface performs satisfactorily in the neighbourhood of the design point.

An important result of reliability calculations is information about the sensitivity of the design point and hence the reliability to variations of parameters or changes in the stochastic behaviour of the variables. This information can be used as a decision tool by providing measures of where to most efficiently allocate resources to increase the reliability of the pipeline.

The parametric sensitivity factor is defined as $\partial\beta/\partial\theta$, where β is the reliability index and θ can be a parameter in the limit state function or a parameter of the distributions of the basic variables. It follows that the updated reliability caused by a change, $\Delta\theta$, can be approximated by

$$\beta(\theta + \Delta\theta) \approx \beta(\theta) + \frac{\alpha\beta(\theta)}{\alpha\beta}\Delta\theta \tag{A.23}$$

Let α_i denote the ith component of the normalized gradient vector to the failure surface in the design point. The quantity α_i^2 is often denoted as an (uncertainty) importance factor that can be interpreted as a relative measure of the significance of the uncertainty of a basic variable (or a group of variables) for the problem considered. The importance factors can then be applied to focus attention on the most important variables.

The omission sensitivity factor gives information about the importance for the reliability of the uncertainty of a stochastic variable. For independent variables, it is given by

$$\gamma_i = \frac{1}{\sqrt{1-\alpha_i^2}} \tag{A.24}$$

The parameter γ_i provides a measure of the relative error in the reliability index if the stochastic nature of an independent variable is ignored. It can be used to reduce the number of quantities that have to be modelled as stochastic variables, and hence to reduce the complexity and the computational time in a reliability analysis.

A.10 Calibration of partial safety factors in the LRFD format

A.10.1 Introduction

The major objective when selecting a design format for calibration is to achieve a uniform safety level for a range of parameter variations and that the format in itself is simple to use in design. The selected design format should be a simplified representation of the actual limit state condition under consideration and then representing the most significant variables entering the design problem. A general description about a calibration methodology may also be taken from Reference [26].

Calibration of partial safety factors in a LRFD format includes the following steps (this holds for both the initial calibration of a design format or a later re-calibration or re-qualification of a design):

- define the scope for the calibration comprising a definition of failure mode(s) and safety class, and target reliability;
- establish the limit state function and the corresponding design equation;
- specify characteristic values for the variables;
- quantify and validate uncertainty measures for the variables;
- estimate a trial set of safety factors reflecting the most important uncertainty sources;
- establish a set of representative design cases utilising the design equation with characteristic values and partial safety factors in compliance with the scope;
- estimate the probability of failure for the design cases and evaluate against the target value.

If the trial set of safety factors tends to provide non-uniform safety levels over a large span of design cases, the final set of safety factors can be obtained by minimizing:

$$\sum_i \sum_j w_{ij} \left(P_{\mathrm{f},ij} - P_{\mathrm{f,target}} \right)^2 = \min \tag{A.25}$$

where

$P_{\mathrm{f},ij}$ is the failure probability for design case j related to failure mode i

w_{ij} is the corresponding weighting factor of the relative frequency of the design.

However, this trial set of safety factors in general results in failure probabilities above the target levels for some cases, and therefore it is necessary to adjust it accordingly.

If only a single safety factor or a product of safety factors enters the limit states, the calibration can be performed as a parametric study on this safety factor within the reliability analysis. With more than one partial safety factor, there is an arbitrariness in selecting the set of partial coefficients leading to designs with the prescribed target reliability. The design point provides a checking point that can be utilised to select partial safety factors, i.e.

$$\gamma_i = \frac{x_i{}^*}{x_i^c} \tag{A.26}$$

where

x^* is the outcome of a stochastic variable and the "*" indicates a design-point value;

c indicates a characteristic value;

i is an index number to indicate the various stochastic variables involved in the formulation.

This definition of the partial safety factors ensures that the design equation recreates the design point.

If the safety factors determined for a large set of different designs show a consistent behaviour, in a given validity range, it is assumed that a generalization can be made. In general, the number of safety factors should be limited. Further, the combination and value of the individual safety factors should be guided by the "design point" co-ordinates and engineering judgement and experience.

It is strongly recommended that assumptions, limitations and design implications versus established industry practice are presented together with the final set of calibrated partial safety factors.

A.10.2 Guidance on design equations

The objective is to establish a simple and practical design format capable of providing a uniform reliability level for a large parameter variation and wide range of design scenarios. The selected design equation should preferably resemble the impact of the most important variables in the limit state function. A general design equation can be given as

$$g\left(S_\mathrm{d}, R_\mathrm{d}, a_\mathrm{d}, \Theta_\mathrm{d}, C, \delta\right) \le 0 \tag{A.27}$$

where

S_d is a design-load value determined from $S_\mathrm{d,I} = S_\mathrm{c,I}\ \gamma_\mathrm{s,i}$. Index c indicates a characteristic value, index d indicates a design value and $\gamma_\mathrm{s,i}$ is the partial safety factor related to load component number i.

R_d is a design capacity determined from $R_\mathrm{d,I} = R_\mathrm{c,I} / \gamma_\mathrm{R,i}$ where $\gamma_\mathrm{R,i}$ is the partial safety factor related to the capacity or strength component number i.

a_d is a design value of geometrical quantities determined from $a_\mathrm{d,I} = a_\mathrm{c,I} \pm \Delta a_\mathrm{i}$ where Δa_i are additive geometrical quantities.

Θ_d is a design value of the model uncertainties not included in the load and capacity variables.

C is a serviceability constraint.

δ is a coefficient accounting for the importance of the pipeline or pipeline element, i.e. accounting for the reliability level required e.g. related to a given safety zone.

The condition for a limit state not to be exceeded can be expressed in the following general form:

$$g\left[\left(\gamma_i\ S_{i\mathrm{c}}\right),\left(\eta_j\ R_{j\mathrm{c}}\right)\right] > 0 \tag{A.28}$$

A very common approach is to introduce at least one partial coefficient associated with the load or load effect and one with the resistance variable. It is further reasonable to distinguish between functional (mainly static) and environmental (mainly dynamic) load effects to get a rational and optimal design format. This is due to uncertainties in the environmental load effects which are typically larger than those in the functional load effects.

A LRFD format can then often be utilized in the form

$$\gamma_\mathrm{E} S_\mathrm{C,E} + \gamma_\mathrm{F} S_\mathrm{C,F} \leqslant \frac{R_\mathrm{C}}{\gamma_\mathrm{R}} \tag{A.29}$$

where

S_C is the characteristic load effect (with subscript “E” and “F” referring to the environmental and functional load respectively);

R_C is the characteristic resistance or material property for the considered failure mode;

γ_E, γ_F and γ_R are calibrated safety factors.

In some cases, it can be convenient to further distinguish between environmental loads arising from different load phenomena or between loads with different magnitude and frequency content.

The design values for load effects and capacity are given by the product of characteristic values and partial coefficients or design factors. If interaction formulas are applied for the pipeline capacity modelling, more than one usage factor can be used to achieve a uniform safety level.

The selected design format should be a simplified representation of the actual limit state condition under consideration and the most significant variables entering the design should be represented.

The design environmental and functional load effects shall be determined by

$$S_\mathrm{D,E} = \gamma_\mathrm{E}\ S_\mathrm{C,E} \tag{A.30}$$

$$S_\mathrm{D,F} = \gamma_\mathrm{F}\ S_\mathrm{C,F} \tag{A.31}$$

and the design value for capacity or strength of the component is found as

$$R_\mathrm{D} = \eta_\mathrm{R}\ R_\mathrm{C} \tag{A.32}$$

Alternatively, strengths of materials can be expressed by their design values, f_D, determined from

$$f_\mathrm{D} = f_\mathrm{C} / \gamma_\mathrm{m} \tag{A.33}$$

Other relevant properties can be treated in a similar way by introducing a partial factor to a characteristic value of the property.

Geometrical parameters shall be expressed by their design values, α_D, defined by the equation

$$\alpha_\mathrm{D} = \alpha_\mathrm{C} \pm \Delta\alpha \tag{A.34}$$

The following symbols are used:

S_{C} is characteristic load effect, where $S_{\mathrm{C,E}}$ and $S_{\mathrm{C,F}}$ are environmental and functional load effects, respectively

R_{C} is characteristic values of component resistance, based on characteristic values of material properties

f_{C} is characteristic values of material properties, for example yield strength

γ_{i} are partial load effect factors. Their values reflect the uncertainties or randomness of the load effect (generally larger than 1,0)

η_{R} is resistance or strength usage factors. Their values reflect the uncertainties of the component resistances including those of material properties and the calculation model if not included otherwise (generally less than 1,0)

γ_{m} are partial material factors. Their values reflect the uncertainties of the material properties (strength and other characteristic properties of the material) and will depend on the actual limit state considered (is often covered by the η_{R} factor)

$\Delta\alpha$ are additive partial geometrical quantities. Their values reflect the uncertainties of the geometrical parameters

A.10.3 Guidance on characteristic values

A.10.3.1 General

The probability of failure depends on the design value of the variables. A change in the definition of the characteristic value that is compensated by a corresponding change in the relevant partial safety factor such that the design value remains the same will not affect the probability of failure. Nevertheless, by a suitable choice of the characteristic values one can reduce the sensitivity of the failure probabilities to changes in the variability of the underlying random variables to achieve a more robust set of LRFD criteria. Generally, this is achieved by defining the characteristic values as fractiles of their probability distributions. The choices can also be guided by the design point from the reliability analysis. From experience, the choices of characteristic values described below have been found to be successful.

A.10.3.2 Material and capacity variables

Characteristic values of material strength parameters, R_{C}, should generally be a low percentile. Typically, an exceedance probability of 1 % to 5 % is appropriate.

For geometrical parameters, the characteristic values usually correspond to the nominal values specified in the design. For parameters that are critical to the overall resistance, however, the characteristic values should also be selected corresponding to a lower percentile of the respective probability distribution, e.g. the minimum steel pipe wall thickness instead of nominal value is applied for pressure containment.

A.10.3.3 Load effect variables

The characteristic values of load effects and other actions, $S_{i,\mathrm{C}}$, are values that should rarely be exceeded. For time-dependent processes, characteristic values are generally given in terms of return values for occurrence, e.g. once in a given reference period.

A.10.3.4 Functional loads

The characteristic value of a functional load is normally taken as the expected annual maximum value.

A.10.3.5 Environmental loads

The characteristic values of environmental load effects for the pipeline under operation are often defined by an annual exceedance probability of 10^{-2} (corresponding to a return period of 100 years). Alternatively, the environmental load effect itself can be defined to have a return period of 100 years if adequate data on the joint occurrence of meteorological and oceanographic conditions so permit and if the partial factors are selected accordingly.

For temporary design conditions (e.g. during construction), the characteristic value should generally be related to the length in time of the condition and is typically selected as three to five times the duration of the condition.

A.10.3.6 Accidental loads

The characteristic value of the accidental load is selected on the basis of a prescribed probability of exceedance. The annual probability of exceedance is normally taken to be less than 10^{-4} per km, unless some other probability of exceedance can be justified.

Since accidental loads can arise from a number of different sources, it can be difficult to accommodate all possible sources within the same LRFD design format, even with a carefully chosen characteristic value of the loads. In such circumstances, it is preferable to perform a structural-reliability analysis that is specific to the type of accidental load considered, or to rely on engineering judgement with traditional safety factors.

Annex B
(informative)

Statistical database — Uncertainty values

B.1 Basic linepipe properties

B.1.1 Database

A statistical database of linepipe properties (uncertainty measures) has been established using data from a range of representative pipe manufacturers [12], [13]. The pipe steel diameter covered in this database varies from about 40 mm to 1 400 mm (1,6" to 56"), the majority in the range of 400 mm to 1 000 mm (16" to 40") (corresponding thickness from 13 mm to 37 mm). The pipe material covers carbon steel as well as duplex steel. Mechanical properties are measured at the specified temperatures for parent metal in both longitudinal and transverse directions, weld metal in the cross-weld direction and the heat-affected zone (HAZ) if relevant. This database with the major findings given below is representative for offshore pipelines.

Requirements for the statistical distribution of materials and geometric parameters, which comply with design requirements and actual distribution of linepipe properties, is given in Reference [2].

B.1.2 Dimensional properties

The dimensional parameters considered include

- wall thickness;
- pipe diameter;
- initial pipe ovality.

Seamless linepipe shall be distinguished from seam-welded linepipe concerning the statistical properties. Seam-welded linepipe is made of plates with more restrictive tolerances, and thus with smaller uncertainties. Uncertainty values are quality- and time-dependent.

The data indicate that the standard deviation in the pipe wall thickness has decreased with improving technology since the 1960s. Although the target standard deviation can vary from one mill to another, samples collected from various mills indicate that the actual standard deviation varies in the range of 0,15 mm to 0,25 mm. The standard deviation is independent of the actual thickness.

Average values based on actual or nominal wall thickness differ from each other. With regard to specifications the actual wall thickness intentionally differs from the nominal wall thickness. This is influenced by several factors, e.g. that tolerances on wall thickness are different from those on mass-per-meter length of linepipe.

The standard deviation of pipe diameter is found to be in the order of two times that of wall thickness for welded pipes; it is in the order of 1/1 000 of the diameter. This indicates that the pipe diameter can be considered as a deterministic parameter, i.e. the coefficient of variation (CoV) is practically zero; see Table B.1. The same conclusion is also applicable to seamless pipes, although the standard deviation is higher. The standard deviation of pipe diameter is (generally) dependent on the wall thickness/diameter ratio and pipe grade.

The pipe ovality, f, is related to the maximum and minimum pipe diameters (D_{max} and D_{min}) measured from different positions around the sectional circumference by

$$f = \frac{D_{\text{max}} - D_{\text{min}}}{D_{\text{max}} + D_{\text{min}}} \tag{B.1}$$

The initial ovality refers to the as-built pipe state when the pipe is free from bending and pressure loading. The mean value is in the order of 0,2 % or less, and the standard deviation is in the order of 0,1 % or less.

Table B.1 presents typical uncertainty values associated with seam-welded pipes. While the pipe diameter can be considered as a deterministic quantity due to negligible uncertainty, the other two parameters have to be considered as random variables. A set of uncertainty values (i.e., fixed mean value and CoV) should generally be linked to pipe manufacturing process, e.g., specifications for manufacturing, and these are typical figures.

Table B.1 — Typical uncertainty values for dimensional properties — Seam-welded pipes

Variable	**Distribution**	**Characteristic value** x_c	**Normalized variable**	CoV = σ/μ %[a]	$(\mu - x_c)/\sigma$
Wall thickness, t	Normal	t_{min}	$X_t = t / t_{min}$	0,5 to 2	2 to 7
		t_{nom}	$X_t = t / t_{nom}$		0 to 2
Pipe diameter, D	Normal	D_{nom}	$X_D = D / D_{nom}$	$< 0,1$	0
Initial ovality, f_0	Lognormal	$f_{0,max}$	—	25 to 60	3 to 15

[a] σ is the standard deviation; μ is the mean value.

For the pipe wall thickness, the lower bound of the CoV can be achieved by top quality steel mills while good quality mills intend to target the mean thickness as close as possible to the minimum value; other mills have to target their mean thickness well above the minimum value (up to 7 standard deviations) in order to reduce the risk of pipes being rejected.

When referring to Table B.1, therefore, conservative values are normally to be selected unless further documentation is provided. It should be emphasized that larger variability can be expected for seamless pipes.

The mean design wall thickness shall be at least 2 standard deviations above the minimum value. In compliance with this requirement, the normalized variable $X_t = t / t_{min}$ can be considered as a normal variable with a CoV of 2 % and a mean value equal to 1,04.

Since the tolerances on wall thickness for welded pipe are generally expressed in millimetres and not in percent, the tolerances expressed by normalized variables (in percent) tend to decrease for increasing mean value of the wall thickness.

B.1.3 Mechanical properties

The mechanical properties considered include

- yield strength;
- ultimate tensile strength;
- stress-strain curve shape, as defined by the hardening parameter;
- Charpy V-notch impact energy;
- critical crack tip opening displacement (CTOD).

Uncertainty values for these parameters depend on the quality of the pipe mill and manufacturing specifications. The CoV of the hoop-yield strength can differ by a factor of 2 across representative samples for different steel grades. It should be noted that the material can show anisotropic behaviour. For pipe produced by expansion in the circumferential direction, yield and tensile strength values for longitudinal direction can be lower than those in transverse direction. The level of anisotropy depends on material grade, chemical composition, rolling conditions and pipe geometry. The tensile strength of the weld is normally required to overmatch that of the parent metal and this is generally consistent in the data.

The fracture toughness properties (Charpy) of the parent metal differ from the weld metal and heat-affected zone (HAZ), but are (rather) independent of the steel grade.

Table B.2 provides typical uncertainty values for mechanical properties. For each parameter, a representative range of variation is given. Conservative values are normally to be selected unless further documentation is provided. For design parameters exhibiting normal distribution mean values are used which are at least 2σ apart from the minimum value, e.g. SMYS, SMTS etc. For parameters such as Charpy V-notch impact energy and CTOD, which do not exhibit normal distributions, a case-by-case basis decision is required.

Table B.2 —Typical uncertainty values for mechanical properties

Variable	**Distribution**	**Characteristic value** x_c	**Normalized variable**	CoV = σ/μ %[a]	$(\mu - x_c)/\sigma$
Yield strength, σ_y	Normal	SMYS	$X_y = \sigma_y/\sigma_{SMYS}$	2 to 6	1 to 4
Tensile strength, σ_u	Normal	SMTS	$X_u = \sigma_u/\sigma_{SMTS}$	1,5 to 6	2 to 10
Charpy energy, C_v	Lognormal	30 J	—	10 to 50	2 to 20
Critical CTOD, δ_{mat}	Beta	0,12 mm	—	30 to 60	2 to 3

[a] σ is the standard deviation; μ is the mean value.

In general, correlation between the mechanical properties in the same pipe joint or correlation of the same mechanical property between pipe joints is weak or negligible except for the following situations:

- moderate correlation of the yield strength among pipe joints made of the same plate;
- moderate correlation of the ultimate tensile strength among pipe joints made of the same plate;
- moderate correlation between the yield and ultimate tensile strengths.

B.1.4 Material fatigue properties

The material fatigue properties are

- crack growth parameters;
- S-N parameters.

The fatigue crack growth rate, da/dN is calculated as follows

$$\frac{da}{dN} = C\left(\Delta K\right)^n \tag{B.2}$$

where

C is a constant;

ΔK is the stress intensity factor range.

If documentation is lacking, values for C and n as given in Table B.3 can be applied for carbon steel. The constant, C, follows a lognormal distribution.

Table B.3 —Typical crack growth parameters for carbon steel

Weld condition	N	C (unit in N, mm)	
	(fixed)	**Mean value**	**CoV**
In air/cathodic protection	3,1	$1{,}1 \times 10^{-13}$	0,55
In seawater	3,5	$3{,}4 \times 10^{-14}$	0,91

A S-N curve is expressed in terms of a linear relationship between log(S) and log(N):

$$\log(N) = \log(K) - m \cdot \log(S) \qquad \text{for } S > S_0 \tag{B.3}$$

where

N is the predicted number of cycles to failure under stress range S;

S_0 is the threshold stress range below which fatigue does not occur;

K is a constant relating to the mean S-N curve and m is the inverse slope of the S-N curve.

For offshore pipelines, three S-N curves are most relevant, namely, “B”-curve for parent material, “C”-curve for seam welds and “F2”-curve for girth welds, as detailed in Table B.4. The constant, K, follows a lognormal distribution.

Table B.4 — S-N curves for carbon steel

Curve	log10(K)			m	S_0 MPa
	Mean value	**Standard deviation**	**Characteristic value**	**(fixed)**	**(fixed)**
B	15,369 7	0,182 1	15,01	4,0	48
C	14,034 2	0,204 1	13,63	3,5	33
F2	12,090 0	0,227 9	11,63	3,0	13

B.2 Maximum internal pressure — Offshore pipelines (landlines not addressed)

The maximum internal pressure is the most important functional load in pipeline structural design. Its probability distribution function can be characterized according to the actual operating practice for pressure setting and control. Two basic pressure levels are commonly set to ensure operational and safety control:

- p_1: pressure level activating the pressure regulating system, normally not exceeding the maximum allowable operating pressure (MAOP);
- p_2: pressure level activating the pressure safety system, not exceeding the maximum allowable incidental pressure (MAIP).

The incidental pressure (pressure surge) is effectively limited by $p_1 \leqslant p \leqslant p_2$, where $p_1 =$ MAOP and $p_2 =$ MAIP.

As incidental events are typically infrequent, their occurrences can be described by a Poisson process. Consequently, the random pressure variable, p, can be modelled by a shifted exponential distribution as follows:

$$F_p(p) = 1 - \exp\left(-\frac{p - p_1}{\lambda}\right) \tag{B.4}$$

where λ is the scale parameter.

Considering that the pressure safety system has a probability of failure not greater than $P_{\mathrm{f,PSS}}$ per pressure surge, $P(p > p_2) = P_{\mathrm{f,PSS}}$, λ can be described as follows

$$\lambda = \frac{p_1 - p_2}{\ln P_{\mathrm{f,PSS}}} \tag{B.5}$$

Incidental events can occur n times a year. The distribution of the annual maximum incidental pressure, p_{max}, is given by

$$F_{p,\mathrm{max}}\left(p_{\mathrm{max}}\right) = \left[F_p\left(p_{\mathrm{max}}\right)\right]^n \tag{B.6}$$

Asymptotically, the above distribution converges to the Type I Gumbel distribution. The mean value and standard deviation of p_{max} are given by

$$\mu_{p,\mathrm{max}} = p_1 + \lambda\left(\ln n + 0{,}577\right) \tag{B.7}$$

$$\sigma_{p,\mathrm{max}} = \frac{\pi}{\sqrt{6}}\lambda \tag{B.8}$$

In reliability analysis, the following normalized uncertainty values for the annual maximum internal pressure can be defined

$$X_p = \frac{p_{\mathrm{max}}}{p_{\mathrm{d}}} \tag{B.9}$$

where p_{d} is the design pressure.

EXAMPLE $P_{\mathrm{f,PSS}} = 10^{-4}$, $n = 12$, $p_2 = 1{,}1 \cdot p_1$ and $p_1 = p_{\mathrm{d}}\ X_{\mathrm{p}}$ can then be considered to follow a Gumbel distribution with a mean of 1,03 and a CoV of 1,4 %. The following recommendation is made: $X_{\mathrm{p}} = G(1{,}03 - 1{,}05;\ 1\text{-}2\%)$.

B.3 Load effects uncertainty — Offshore pipelines

For some variables sufficient experience is available as a basis for recommendation of distribution types and sometimes also for recommendation of distribution parameters. A list of environmental load variables with their recommended distribution types is given in Table B.5.

Apart from accidental load effects, all load effects are partitioned into functional load effects and environmental load effects. In general, uncertainty measure for a specific load effect can be expressed in a normalized form as

$$X_{\mathrm{E}} = \frac{S_{\mathrm{E}}}{S_{\mathrm{E,c}}} \tag{B.10}$$

or

$$X_{\mathrm{F}} = \frac{S_{\mathrm{F}}}{S_{\mathrm{F,c}}} \tag{B.11}$$

where

S_{E} and S_{F} are stochastic environmental and functional load effects;

$S_{\mathrm{E,c}}$ and $S_{\mathrm{F,c}}$ are characteristic environmental and functional load effects;

X_{E} and X_{F} are normalized environmental and functional load effects.

The mean value of X_{E} or X_{F} is often called a bias.

Table B.5 — Environmental load variables and corresponding distribution types

Variable name	Load variable	Distribution type
Wind	Short-term instantaneous gust speed	Normal
	Long-term n-minute average speed	Weibull
	Extreme speed, annual	Gumbel
Waves	Short-term instantaneous surface elevation (deep water)	Normal
	Short-term wave heights	Rayleigh
	Wave period	Longuet-Higgins
	Long-term significant wave height	Weibull
	Long-term mean zero-up-crossing or peak period	Lognormal
	Joint significant height/mean zero up-crossing or peak wave period	3-parameter Weibull (height)
	Lognormal period conditioned on height	
	Extreme wave height, annual	Gumbel
Current	Long-term velocity	Weibull
	Extreme velocity, annual	Gumbel
Forces	Hydrodynamic coefficients	Lognormal

Due to the random nature of the ocean environment, the variability (CoV) in an environmental load effect is normally much larger than that in a functional load effect. In situations where the pipe is subjected to bending, the pipeline configuration is classified as either load-controlled (LC) or displacement-controlled (DC). In load-controlled situations, the bending effect is represented by the bending moment while it is represented by the bending strain in displacement-controlled situations. The variability of the bending moment is different from that of the bending strain in the region where the moment-strain relationship is non-linear.

The bias depends on the definition of the characteristic load effect. Functional load effects can be considered as unbiased, as the corresponding characteristic values are defined as the expected maximum. Environmental load effects can be assumed as unbiased for pipelines during installation. If the operation phase is of concern, the bias of an environmental load effect is defined by the ratio of mean annual maximum value to 100-year return period characteristic value, which is normally in the order of 0,6 to 0,8.

Table B.6 provides typical uncertainty values for the functional and environmental load effects in different pipeline conditions and phases. Conservative values are normally selected unless further documentation is provided [13].

Table B.6 — Typical uncertainty measures for normalized load effects

Pipeline phase	x_{F}	x_{E}	Condition
Installation, reeling	1,0	—	DC
Installation, overbend	N(1,0; 5-10%)	G(1,0; 40-60%)	DC
Installation, stinger tip	N(1,0; 5-15%)	N(1,0; 40-60%)	LC
Installation, sagbend	N(1,0; 5-10%)	N(1,0; 20-40%)	DC/LC
On-bottom, temporary	N(1,0; 10-20%)	N(0,6-1,0; 20-40%)	DC/LC
On-bottom, operating	N(1,0; 10-20%)	N(0,6-0,8; 20-40%)	DC/LC

NOTE G(1,0;40-60%) denotes a Gumbel distribution with a mean value equal to 1,0 and a CoV in the range of 40 % to 60 %. N(0,6-1,0; 5-10%) denotes a normal distribution with a mean in the range of 0,6 to 1,0 and a CoV in the range of 5 % to 10 %.

Annex C
(informative)

Target safety levels — Recommendations

C.1 General

Several methods for calculation of target safety or risk levels exist and can be used. This annex illustrates how the selection of target safety levels can be done for on land and offshore pipelines.

Determination of appropriate target safety levels is fundamental to the process of developing reliability-based design and operational guidelines through the application of reliability analysis and calibration of design equations. However, to be appropriate, it is necessary that the hypothesis, the method of calculation and the target levels be consistent among the various applications.

Traditional design methods provide adequate average safety levels for pipelines; however, significant variation in safety levels can exist from one case to another. The objective of reliability-based design is to provide a uniform safety level across all design cases. This can be achieved by meeting predetermined target safety levels, such as those given in this annex.

The evaluation of the target safety levels for pipelines should primarily be based on information about the implied safety in traditional pipeline design methods, using appropriate uncertainty measures from the time the code was made. Further, the actual consequences, in terms of the potential for human injury, environmental damage and economic losses, should be taken into account. This is done in this International Standard by classifying the pipeline into safety classes based on the failure consequences and hazard potential.

The selected target levels may also be compared with pipeline failure statistical data and target safety measures defined in other structural codes; however, this is mainly for relative comparison and the implied safety level in traditional design practice should be the main selection criteria.

For both offshore and on-land pipeline applications, it is appropriate to control the probability of failure (P_f) as a function of the consequences as established by the safety class designation given herein. With no explicit risk and/or safety level available, the equivalent target failure probabilities versus safety class and limit state category can be taken from C.5 for both offshore and on-land pipelines. However, the figures given herein should not be utilized without a deeper evaluation of their applicability for the specific case.

C.2 Principles for selecting target safety levels

Pipeline failures and related uncertainties can be categorized as follows:

- calculated risk associated with normal uncertainties;
- human errors;
- unknown phenomena.

Loads and resistance are subject to fundamental random variability and normal uncertainties due to lack of knowledge. Failure occurs when the random load exceeds the random resistance. The probability of failure is then controlled by using partial safety factors in SLS, ULS and FLS design. These normal (fundamental) uncertainties are accounted for in the structural failure calculation.

Human errors differs from that of natural phenomena and normal uncertainty, and different safety measures are required to control error-induced risk. Primarily, quality assurance and control procedures, such as inspection and repair of the structure during fabrication and operation, should be used to control human errors.

In addition, some accident scenarios develop over time and can be detected by an operational management system.

If all causes of accidents were considered in estimating the risk, the desirable safety level by using a certain target level can be achieved exactly. However, in structural reliability analysis, only normal uncertainties in loads and resistance properties are considered and the resulting failure probability is, for this reason, often denoted notional or nominal and can be different to the observed failure rates. The effect of human errors is thus not taken into account.

Unknown phenomena in loading, resistance and failure modes cannot be explicitly considered in design and might be addressed by further R&D activities. The safety target, thus, does not account for unknown phenomena.

C.3 Pipeline failure data

C.3.1 General

Historical failure rates can be used to set target safety levels for pipelines on a relative basis and are used herein as a guideline for the final selection as noted above.

Before the failure data are reviewed and their implication on the target safety level is inferred, it is necessary first to examine the causes of structural failures and how the risk associated with these causes can be measured by risk and reliability analysis.

In general, the main causes of pipeline failure can be summarized as follows:

- line failure due to faulty material, construction or weld defects, fatigue, corrosion and other material degradation mechanisms;
- external damage due to the third-party activities, such as anchors and dropped objects for offshore pipelines, and excavation activities for on-land pipelines; and
- mechanical failure of ancillary equipment such as valves and couplings.

The probability of failure depends on a number of parameters, including pipeline location, pipeline size, transported fluid category, pipeline age and pipeline protection measures. For example, a large-diameter pipeline with a heavy wall thickness has much greater resistance to external damage than a small-diameter pipeline, and a gas pipeline is less likely to have internal corrosion damage than an oil pipeline. Hence, consideration of these aspects is essential in evaluation of the pipeline failure data.

C.3.2 Offshore pipelines

Data and analyses for the North Sea have been performed by several organizations. An incident database for North Sea pipelines, PARLOC, has been established for the UK Health and Safety Executive (HSE); see Reference [14]. The database provides the most complete information based on approximately 160 000 pipeline km years and approximately 10 000 risers. The total number of incidents reported to the end of 1993 was 401, comprising 292 for operating lines and 109 for non-operating lines. The 292 incidents involved 174 and 118 incidents with pipelines and fittings, respectively. Among the 174 incidents to operating pipelines, about 30 % involved leaks and loss of containment. The major cause for the loss of containment is corrosion (52 %) with external impact (anchors, trawl and installation) as the next most significant cause (28 %). The loss of containment frequency is thus found to be in the order of

- 10^{-4} per km and year on average for all steel pipelines;
- 10^{-3} per year for very short lines and for the safety zone;
- 10^{-4} to 10^{-5} per km and year for the larger diameter and the very long lines.

It is noted that the loss of containment frequency indicates some sensitivity to several factors. For instance, the frequency due to anchoring/impact in the midline location decreases with increasing diameter and thickness. The frequency of anchoring/impact incidents for trenched/buried pipelines is smaller than that of the exposed pipelines.

The failure statistics reported for the Gulf of Mexico are in agreement with that in the North Sea.

It should be noted that the experienced failure/accident rate cannot be directly compared with failure probabilities calculated by structural reliability analysis, which may include uncertainties different from those causing the failures.

Accidental events or conditions can be caused by gross fabrication and operational errors. Hence, the target level for ALS criteria can be compared with experienced accident/failure rates. Even if the experienced risk level is acceptable, the target failure probability level for ALS should normally be smaller than the experienced probabilities. This is because the ALS criterion refers to consequences beyond those represented by the cases represented in the database.

The fact that the experienced failure rates in the near-platform zone is significantly larger than that in the off-platform zone should not necessarily be reflected in the target levels. On the contrary, the target probability for the near-platform zone should be smaller than the off-platform zone due to more severe consequences of failure. This fact demonstrates that accident statistics should be used with care and that limited information about specific target levels can be deduced from the accident experiences.

Therefore, with an experienced loss of containment frequency of the order 10^{-3} to 10^{-4} per year per km, the following target levels are reasonable:

- 10^{-5} to 10^{-6} per year and km for the ALS condition;
- 10^{-3} to 10^{-5} per pipeline per year for the ULS condition.

C.3.3 On-land pipelines

For on-land pipelines, historical failure rate data are considered to be directly comparable to calculated failure probabilities, provided that the major failure causes (corrosion and external damage) are considered in sufficient detail.

Two sets of historical failure rate data that can be considered for validation purposes are the U.S. Department of Transportation (DOT) data for transmission and gathering pipelines; and the [27] European Pipeline Incident Data Group (EGIG)data for gas transmission lines [28]. The DOT data are for the years 1985 to 1995, with a total exposure of 6 000 000 km-years. The EGIG data cover the years 1970 to 1998, with a total exposure of 2 100 000 km-years. Members of the EGIG are required to report all transmission line failure, including leaks, while the DOT requires that only those failures meeting a certain criterion be reported (e.g. injury and/or property damage exceeding $50 000 US). Because of this difference, some researchers [15] have suggested that the DOT failure rates be multiplied by a factor of four to account for unreported incidents.

The average failure rates determined for DOT and EGIG for on-land gas pipelines are summarized in Tables C.1 and C.2 [16].

Table C.1 — On-land gas transmission line historical failure rates

Failure cause	**DOT-reportable × 4**		**EGIG:2001**	
	Failure rate per km-yr	% of total	**Failure rate** per km-yr	% of total
External corrosion	$0{,}64 \times 10^{-4}$	15	$0{,}53 \times 10^{-4}$	12
Equipment impact	$2{,}10 \times 10^{-4}$	50	$2{,}20 \times 10^{-4}$	50
All other	$1{,}45 \times 10^{-4}$	35	$1{,}67 \times 10^{-4}$	38
Total	$4{,}19 \times 10^{-4}$	100	$4{,}40 \times 10^{-4}$	100

Table C.2 — On-land gas transmission line historical failure rates, large leaks and ruptures only
(pin-hole leaks omitted)

Failure cause	DOT-reportable		EGIG:2001	
	Failure rate per km-yr	% of total	**Failure rate** per km-yr	% of total
External corrosion	$0{,}16 \times 10^{-4}$	15	$0{,}03 \times 10^{-4}$	1
Equipment Impact	$0{,}51 \times 10^{-4}$	49	$1{,}61 \times 10^{-4}$	75
All other	$0{,}37 \times 10^{-4}$	36	$0{,}52 \times 10^{-4}$	24
Total	$1{,}04 \times 10^{-4}$	100	$2{,}16 \times 10^{-4}$	100

Base on these historic data, it is reasonable to suggest that appropriate overall average failure rate targets (across a wide spectrum of design cases) are on the order of 3×10^{-4} to 4×10^{-4} for all failures, and 1×10^{-4} to 2×10^{-4} for large leaks and ruptures.

C.4 Safety levels in structural design codes

Target safety levels for civil structures and offshore platforms have been well defined, specified or recommended by relevant authorities or institutions.

For example, the model code issued by the Nordic Committee for Safety of Structures [17], specifies annual target failure probabilities for building structures in the range of 10^{-3} to 10^{-7} per year depending upon the failure mechanism and consequences of failure. It is not clear whether these target values refer to components or also reflect the system characteristics. In a later issue (1985) of this document, the target level is specified in the range 10^{-4} to 10^{-6} depending only upon the consequences of failure. It is noted that very high target safety levels are required for very serious consequences of failure, which implicitly refer to human death. Considering also social aspects in addition to economical aspects, high target safety levels are generally adopted even for less serious consequences of failure. When civil structures are compared with pipelines, it might be argued that pipeline sections in populated areas (i.e. the near platform zone for offshore pipelines and Class 2, 3 and 4 areas for on-land pipelines) should have similar target failure probabilities, i.e., on the order of 10^{-5} to 10^{-7}. Other direct comparisons might not be appropriate.

Offshore platforms resemble offshore pipelines more than civil structures, because the consequences of failure can imply severe environmental damage. The target safety levels for pipelines should thus be more closely related to those for platforms.

The first offshore code, which explicitly specifies design target safety levels for platforms, is Reference [18]. The annual target failure probabilities are given in accordance with the consequences of failure, which range from 10^{-5} for great risk to human safety or high potential for environmental pollution or damage to 10^{-1} for impaired function or unserviceability. These target values are used to calibrate the partial safety factors in the CSA code.

In design of offshore structures, the API and NPD codes are widely applied. No specification of target safety levels is given in these codes. However, research efforts have been made to estimate implied target safety levels in these codes, which are regarded as satisfactory from past experience. For load-bearing offshore structures, the NPD regulations refer to a target safety level of 10^{-4} to 10^{-5} per year for structural members, Reference [19].

Comparing the specified and implied safety levels in these commonly applied design codes for offshore platforms, it can be concluded that the Reference [18] specification gives a rational range of target safety levels, i.e., 10^{-1} to 10^{-5}, though more refined safety classes applicable to offshore pipelines might be needed.

The Dutch authority [20], specifies an acceptance level of 10^{-6} per km per year regarding collapse of a pipeline under accidental load. This level is not required for other load conditions. The Danish authority specifies an allowable pipe leak level of 10^{-4} per year per km. Although no other quantitative specification has been found, these two levels together with safety levels for other structures provide another basis for establishing target safety levels for offshore pipelines considering various limit states and corresponding consequences of failure.

C.5 Recommended target safety levels

C.5.1 General

The implied safety level achieved by current design practice should primarily be used for the definition of target safety provided that the average implied safety is considered to be appropriate. The implied safety for various limit states using current design practice has been estimated through various technical studies, e.g. selection of target safety levels for offshore pipelines follows the general recommendations given in Sotberg[21], [22], with a particular focus on the implications on updated statistical data and technical models, while the technical basis for on-land pipelines follows the approach given in References [16], [23] and [24].

C.5.2 Offshore pipelines

For offshore pipelines, the acceptable failure probabilities as given in Table C.3 should be applied if no other case-specific information is given. These figures are consistent with the average implied safety level in current design practice and adjusted to account for the consequence of failure. It is also noted that the target safety levels as recommended compare well with the failure statistics and are rational in comparison to other structural codes.

Table C.3 — Acceptable failure probabilities vs. safety class, offshore pipelines

Limit state	Probability bases	Safety classes			
		Low	Normal	High	Very high
SLS[a]	Annual per km	10° to 10^{-1}	10^{-1} to 10^{-2}	10^{-2} to 10^{-3}	NA
ULS	Annual per pipeline	10^{-3}	10^{-4}	10^{-5}	NA
FLS[b]					
ALS[c]					

[a] The failure probabilities provided for SLS are not mandatory. SLS may be used to select operational limitations and can be defined according to the operator preference. Exceeding the SLS conditions require a subsequent ALS design check.

[b] The FLS probability basis is failures per year, i.e., normally the last year of service life or the last year before inspection (the reference is the lifetime failure rate if no inspection is performed).

[c] Refers to the overall allowable probability of severe consequences, including incident probability, e.g. $P = P_{\phi|E}\, P(E)$

C.5.3 On-land pipelines

Different approaches can be used to select safety or risk levels for on-land pipelines. Factors that need to be considered in selecting these targets include the type of fluid, population density (or location class), pressure and diameter.

C.5.3 describes one approach [24], [25] that has been used to develop reliability targets for onshore natural gas transmission pipelines. The key assumptions made in developing these targets are described to allow the designer to evaluate their applicability on a case-by-case basis.

This approach is based on the maximum acceptable total failure rate for all failure causes combined. The target reliability curves for each safety class are intended to limit societal risk. They can be obtained by combining historical failure frequencies (see C.3) and considerations about possible incident impact.

Risk analysis has been used to determine the reliability levels required to ensure that the actual risk levels can be tolerated by society. The selected targets satisfy two risk criteria:

- acceptable societal risk, as measured by the expected number of fatalities (due to incidents) per kilometre year of exposure, assuming that population is uniformly distributed in the vicinity of the pipeline; and
- acceptable individual risk, defined as the risk of fatality for a person located on the pipeline alignment.

Tolerable risk levels were established hereinafter by assuming that the overall average risk level for current pipelines in North America is considered acceptable. Based on this, the tolerable societal risk levels were selected to match the average societal risk level for all pipelines. These levels were estimated by calculating risk for a broad spectrum of pipeline design cases (i.e. different pressures, diameters, steel grades and class locations), designed according to the existing ASME gas pipeline design code [25] and maintained according to the ASME standard for managing pipeline integrity [25]. Based on a review of published guidelines, the tolerable individual risk levels were selected as 10^{-4} in Class 1, 10^{-5} in Class 2 and 10^{-6} in Classes 3 and 4.

Target reliability levels were then selected to provide a constant level of societal risk, equal to the calculated tolerable value, for all design conditions. This produced a set of constant-risk, target reliability curves, one for each location class, that vary the required reliability level as a function of pipe size and design pressure; i.e. the required reliability changes according to failure consequences as measured by the number of people affected. A lower bound reliability curve was also developed to limit the level of individual risk experienced by a single person located on the pipeline alignment.

The primary criterion used to set target reliability levels in this approach was to achieve an average societal risk level of 2×10^{-5} per km-year, while maintaining an approximately constant risk level.

It is assumed that the possible consequences decrease as a function of $P \cdot D^3$, because the failure consequences for a given class increase as a linear function of the expected number of people affected, that is with a) with the size of the affected area, which is proportional to $P \cdot D^2$, and b) the probability of ignition, which is assumed to be roughly proportional to D.

The following equations relating the failure rate to the class location system are found: [25]

Safety class 1(low)
$$P_{\text{f,target}} = \frac{5 \times 10^{-3}}{P \cdot D^3} \tag{C.1}$$

Safety class 2 (medium)
$$P_{\text{f,target}} = \frac{5 \times 10^{-4}}{P \cdot D^3} \tag{C.2}$$

Safety class 3 (high)
$$P_{\text{f,target}} = \frac{5 \times 10^{-5}}{P \cdot D^3} \tag{C.3}$$

Safety class 4 (very high)
$$P_{\text{f,target}} = \frac{5 \times 10^{-6}}{P \cdot D^3} \tag{C.4}$$

Individual risk
$$P_{\text{f,target}} = \frac{5{,}2 \times 10^{-4}}{\left(P \cdot D^3\right)^{0{,}66}} \tag{C.5}$$

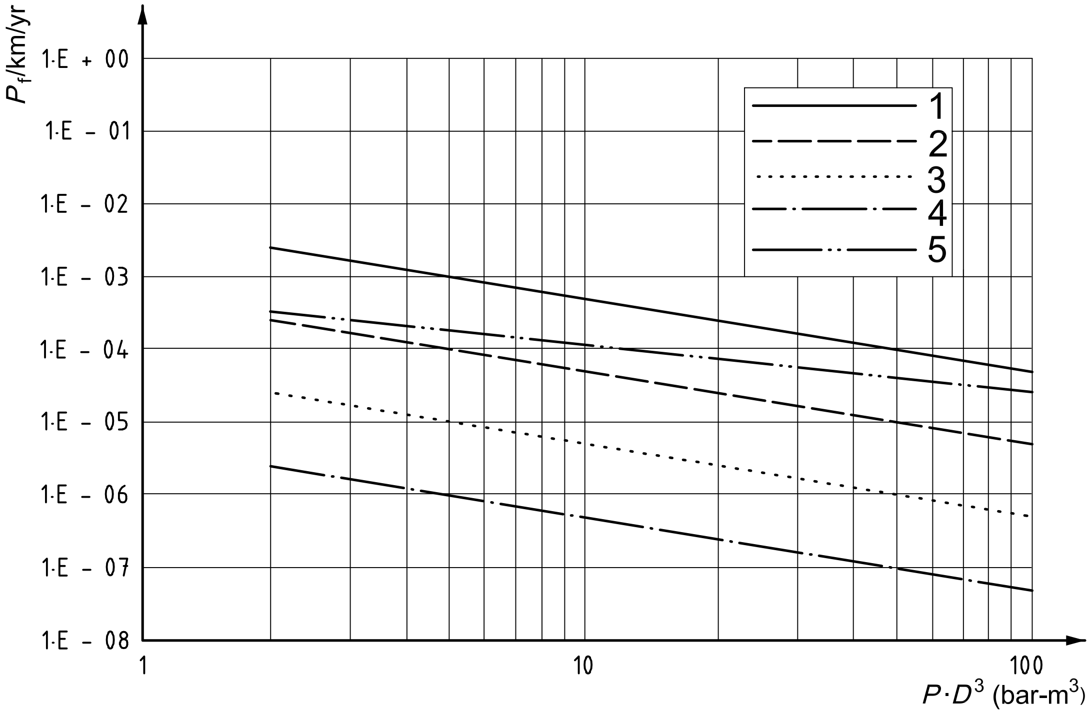
where

$P_{\text{f,target}}$ is the maximum acceptable failure probability in failures per kilometre per year (excluding small leaks);

P is the internal pressure in bars;

D is the outside pipe diameter in metres.

The resulting set of recommended target reliability curves is given, in Figure C.1 (where a direct correspondence has been assumed between the ASME class locations and the safety classes used in this document) and can be applied, for ULS, FLS and ALS. For SLS, the failure probabilities given in Table C.3 can be used. The probability basis is failures per kilometre per year. For temporary conditions, the actual period can be applied if less than 1 year.



Key

1 safety class 1(low) from Table C.3
2 safety class 2 (medium) from Table C.3
3 safety class 3 (high) from Table C.3
4 safety class 4 (very high) from Table C.3
5 individual risk from Equation C.5

Figure C.1 — Acceptable failure probabilities, on-land pipelines, ULS, FLS, ALS

State-of-the-art models and conservative simplifying assumptions were used to develop the target reliability levels described above. As such, the targets are seen as generally conservative, with the degree of conservatism varying from case to case. Sources of conservatism that may be further examined include the following.

— The targets are to be met at all times during the design life of the pipeline. Since reliability decreases with time due to deterioration mechanisms, and increases immediately after rehabilitation events (e.g., inline inspection and repair), the critical points in time to meet the targets are just before a rehabilitation event. Since the failure rate is kept below the target at the minimum reliability points, the average failure rate over the design life is lower than the target.

— The targets are designed to match the safety associated with new pipelines that are maintained according to best practice. Therefore, they lead to lower failure rates than historically observed for existing pipelines.

Based on this, it is suggested that detailed analyses can be used in some cases to produce less conservative target levels.

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