DNV

RECOMMENDED PRACTICE

DNV-RP-F101

Edition September 2019
Amended September 2021

Corroded pipelines

DNV AS

FOREWORD

DNV recommended practices contain sound engineering practice and guidance.

Any comments may be sent by e-mail to *rules@dnv.com*

CHANGES – CURRENT

This document supersedes the January 2015 edition of DNV-RP-F101.

The numbering and/or title of items containing changes is highlighted in red.

Amendments September 2021

Topic	*Reference*	*Description*
Rebranding to DNV	All	This document has been revised due to the rebranding of DNV GL to DNV. The following have been updated: the company name, material and certificate designations, and references to other documents in the DNV portfolio. Some of the documents referred to may not yet have been rebranded. If so, please see the relevant DNV GL document. No technical content has been changed.

Changes September 2019

This document is a republished version of the May 2017 edition. No changes have been made to the content of this document.

Changes May 2017

The purpose of the revision of this service document is to comply with the new DNV GL document reference code system and profile requirements following the merger between DNV and GL in 2013. Changes mainly consist of updated company name and references to other documents within the DNV GL portfolio.

Some references in this service document may refer to documents in the DNV GL portfolio not yet published (planned published within 2017). In such cases please see the relevant legacy DNV or GL document. References to external documents (non-DNV GL) have not been updated.

Editorial corrections

In addition to the above stated changes, editorial corrections may have been made.

Changes - current

Acknowledgements

This recommended practice is based upon a project guideline developed in a co-operation between BG Technology and DNV GL.

The results from their respective joint industry projects (JIP) have been merged and form the technical basis for this recommended practice.

We would like to take this opportunity to thank the sponsoring companies/organisations for their financial and technical contributions (listed in alphabetical order):

— BG plc

— BP Amoco

— Health and Safety Executive, UK

— Minerals Management Service (MMS)

— Norwegian Petroleum Directorate (NPD)

— PETROBRAS

— Phillips Petroleum Company Norway and Co-Ventures

— Saudi Arabian Oil Company

— Shell UK Exploration and Production, Shell Global Solutions, Shell International Oil Products B.V.

— Statoil

— Total Oil Marine plc

DNV GL is grateful for valuable co-operations and discussions with the individual personnel of these companies.

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Contents

SECTION 1 GENERAL

1.1 Introduction

This recommended practice (RP) document provides recommendations for assessing pipelines containing corrosion defects subjected to:

— internal pressure loading only
— internal pressure loading combined with longitudinal compressive stresses.

Two alternative approaches to perform the assessment of corrosion defects are described, and the document is divided into two parts. The main difference between the two approaches is in their safety philosophy:

— The first approach, given in Sec.3 (part A), includes calibrated safety factors taking into account the natural spread in material properties, wall thickness and internal pressure variations. Uncertainties associated with the sizing of the defect and the specification of the material properties are specifically considered in the determination of the pressure resistance (capacity). This part of the recommended practice is also a supplement to DNV-ST-F101. Probabilistically calibrated equations (with partial safety factors) for the determination of the pressure resistance of a corroded pipeline are given.
— The second approach, given in Sec.4 (part B), is based on the Allowable Stress Design (ASD) format. The failure pressure (capacity) of the corrosion defect is calculated, and this failure pressure is multiplied by a single usage factor based on the original design factor. Consideration of the uncertainties associated with the sizing of the corrosion defect is left to the judgement of the user.

1.2 BG plc and DNV research projects

The first issue of this document was a result of co-operation between BG Technology (part of BG plc) and DNV. The results from their respective joint industry projects were merged, and formed the technical basis for this recommended practice (/3/, /4/ and /15/).

The BG technology project generated a database of more than 70 burst tests on pipes containing machined corrosion defects (including single defects, interacting defects and complex shaped defects), and a database of linepipe material properties. In addition, a comprehensive database of 3D non-linear finite element analyses of pipes containing defects was produced. Criteria were developed for predicting the remaining strength of corroded pipes containing single defects, interacting defects and complex shaped defects.

The DNV project generated a database of 12 burst tests on pipes containing machined corrosion defects, including the influence of superimposed axial and bending loads on the failure pressure. A comprehensive database of 3D non-linear finite element analyses of pipes containing defects was also produced. Probabilistic methods were utilised for code calibration and determination of partial safety factors.

1.3 Update year 2014

This update of the recommended practice includes:

— Improved guidance on how to perform a probabilistic assessment ([2.8] and new App.E).
— New guidance regarding consideration of corrosion development (new [2.9]).
— Improved guidance on how to account for system effects ([3.6]).
— A new assessment methodology for pipelines with river bottom corrosion including assessment of detailed inspection data and estimation of corrosion rates ([3.9] and new App.D).
— Reduced conservatism in the method for interacting defects ([3.8]).

— Better compliance with the DNV-ST-F101:

  — Pressure definitions ([1.13])
  — Application of the term pressure resistance (Sec.2 and throughout part A and relevant appendices) instead of a number of different versions of the term allowable operating pressure
  — [2.6] Characteristic material properties
  — [3.3] Partial safety factors and fractile values
  — [3.4] Circumferential corrosion (partial safety factors)
  — [3.7] Supplementary material requirements in the previous revision has been removed and is now covered by [2.6]
  — [3.7.2] Acceptance criteria
  — [3.7.3.1] Pressure resistance equation, and
  — [3.7.3.2] Alternative applications.

The updates are mainly a result of joint industry efforts together with ConocoPhillips, DONG, Exxon Mobil, Petrobras, Statoil, Total E&P UK and Woodside. The new assessment methodology for pipelines with river bottom corrosion (App.D) is mainly based on an earlier joint industry project between DONG, Statoil and DNV. Furthermore, improvement of the method for interacting defects was based on valuable input from the joint industry project on mixed type of interaction (MTI) headed by Petrobras /21/ - /24/.

1.4 Application

The methods provided in this document are intended to be used on corrosion defects in carbon steel pipelines (see [1.6] - not applicable for other components) that have been designed to the DNV standard DNV-ST-F101*Submarine pipeline systems*, /8/ or other recognised pipeline design code as e.g. ASME B31.4 /1/, ASME B31.8 /2/, PD 8010 /5/, IGEM/TD/1 /9/, ISO/DIS 13623 /10/, CSA Z662-94 /7/, provided that the safety philosophy in the design code is not violated.

When assessing corrosion defects, the effect of continued corrosion growth should be considered. If a (highly) corroded region shall be left in service, then measures should be taken to arrest further corrosion growth, and/or an appropriate inspection and monitoring programme should be adopted to monitor any further development – see [2.9].

This recommended practice does not cover every situation that requires a fitness-for-purpose assessment and further methods may be required.

1.5 Structure of document

This recommended practice describes two alternative approaches for assessing corrosion defects. The first approach is given in part A, which consists of Sec.3. The second approach is given in part B, which consists of Sec.4.

A flow chart outlining a simple overview of the assessment procedure (for both part A and part B) is shown in Figure 1-1.

Worked examples are given in App.A for the methods described in part A and App.B for the methods described in part B.

App.C presents detailed calculation of measurement accuracies.

App.D presents the assessment methodology for pipelines with long axial corrosion defects.

App.E presents the detailed burst capacity equation.

1.6 Applicable defects

The following types of corrosion defect can be assessed using this document:

— internal corrosion in the base material
— external corrosion in the base material

— corrosion in seam welds
— corrosion in girth welds
— colonies of interacting corrosion defects
— metal loss due to grind repairs (provided that the grinding leaves a defect with a smooth profile, and that the removal of the original defect has been verified using appropriate NDT methods).

When applying the methods to corrosion defects in seam welds and girth welds, it should be demonstrated that there are no significant weld defects present that may interact with the corrosion defect, that the weld is not undermatched, and that the weld has an adequate toughness (see [1.8]).

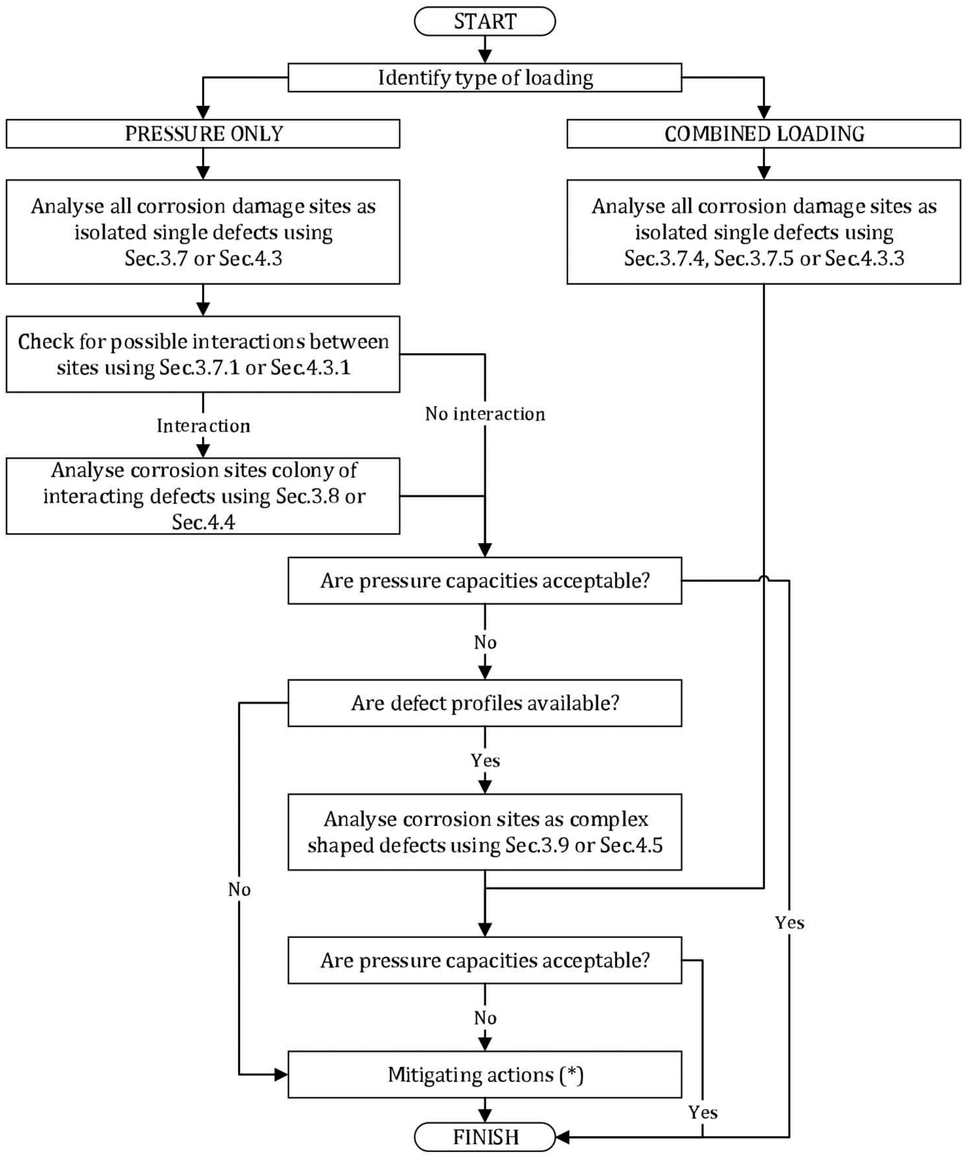

Figure 1-1 Flowchart of the assessment procedure

* Examples of mitigation actions are: more detailed analysis using other methods, modifying internal content condition (e.g. re-defining pressure limits, changing content, changing inhibitors), or ultimately repairing the pipeline. Mitigation actions are not covered by the recommended practice.

1.7 Applied loads

Internal pressure, axial and bending loads may influence the failure of a corroded pipeline. The following combinations of loading and defects are covered by this recommended practice:

Internal pressure loading for:

— single defects
— interacting defects
— complex shaped defects.

Internal pressure loading and combined with longitudinal compressive stresses for:

— single defects.

The compressive longitudinal stress can be due to axial loads, bending loads, temperature loads etc.

The recommendations given in this document are confined to the effects of internal pressure and compressive longitudinal loading on longitudinal failure because the validation of these effects was addressed in the DNVand BG Technology projects.

The behaviour of corrosion defects under combined internal pressure and bending loads, and/or tensile longitudinal loads, was outside the scope of the DNV and BG Technology projects and, therefore, this loading combination has not been included as part of the recommended practice. Methods for assessing defects under such loading cases are recommended in other documents (e.g. /6/ and /11/).

1.8 Exclusions

The following are outside the scope of this document (for validation of method, see [1.12]):

1) Materials other than carbon linepipe steel.
2) Linepipe grades (see API 5L, /14/ and DNV-ST-F101 Sec.13/8/) in excess of X80 [1)].
3) Cyclic loading.
4) Sharp defects (i.e. cracks) [2)].
5) Combined corrosion and cracking.
6) Combined corrosion and mechanical damage.
7) Metal loss defects attributable to mechanical damage (e.g. gouges) [3)].
8) Fabrication defects in welds.
9) Defect depths greater than 85% of the original wall thickness (i.e. remaining ligament is less than 15% of the original wall thickness).

The assessment procedure is only applicable to linepipe steels that are expected to fail through plastic collapse. Modern pipeline steel materials normally have sufficient toughness to expect plastic collapse failure. Studies have recommended Charpy V-notch value as lower bound for the material toughness for plastic collapse /17/ and /18/.

The procedure is not recommended for applications where fracture is likely to occur. These may include:

1) Materials with Charpy values less than 27 J (20 ftlbf) full size test (equivalent 2/3 scale is 18 J, 13 ftlbf). For the weld a minimum full size Charpy value of 30 J is recommended.
2) Any material that has been shown to have a transition temperature above the operating temperature.
3) Material of thickness greater than 12.7 mm (1/2"), unless the transition temperature is below the operating temperature.
4) Defects in bond lines of flash welded (FW) pipe.
5) Lap welded or furnace butt welded pipe.
6) Semi-killed steels.

1)	The validation of the assessment methods comprised full scale tests on grades up to X65. For grades up to X80 (inclusive), only material tests and finite element analysis were performed.
2)	Cracking, including environmentally induced cracking such as SCC (stress corrosion cracking), is not considered here. Guidance on the assessment of crack-like corrosion defects is given in References /8/ and /9/.
3)	Metal loss defects due to mechanical damage may contain a work hardened layer at their base and may also contain cracking.

1.9 Other failure modes

Other failure modes, such as buckling, wrinkling, fatigue and fracture, may need to be considered. These failure modes are not addressed in this document, and other methods may be applicable (/6/, /11/, and /13/).

1.10 Tiered approach and further assessment

The intent of this recommended practice is to provide tiered procedures for the assessment of corroded pipe. The first tier level is the simplified approach for single defect assessment, where total length and maximum depth of the defect and the material specification are used.

If the defect is not found to be acceptable a more refined assessment including the profile of the defect can be performed, provided that information of the profile is available.

Furthermore, if the corrosion defects are still not found to be acceptable using the procedures given in this recommended practice, the user has the option of considering an alternative course of action to more accurately assess the remaining strength of the corroded pipeline. This could include, but is not limited to, detailed finite element analysis, probabilistic assessments and/or full scale testing, and is outside the scope of this document. If such an alternative course is selected, the user should document the reliability of the results.

1.11 Responsibility

It is the responsibility of the user to exercise independent professional judgement in application of this recommended practice. This is particularly important with respect to the determination of defect size and associated sizing uncertainties.

1.12 Validation

The methods given in this recommended practice for assessing corrosion under only internal pressure loading have been validated against 138 full scale vessel tests, including both machined defects and real corrosion defects. The range of test parameters is summarised below:

Pipeline			
Pipe diameter, mm	219.1 (8")	to	914.4 (36")
Wall thickness, mm	3.40	to	25.40
D/t ratio	8.6	to	149.4
Grade (API/5L)	X42	to	X65
Defects			
d/t	0	to	0.97
$l/(Dt)^{0.5}$	0.44	to	35

c/t (circumferential)	0.01	to	22

(Shortest defect was *l* = 2.1 t)

For nomenclature, see [1.14].

The method for assessing corrosion defects under internal pressure and compressive longitudinal loading has been validated against seven full scale tests on 324 mm (12 inch) nominal diameter, 10.3 mm nominal wall thickness, Grade X52 linepipe.

The method for assessing fully circumferential corrosion under internal pressure and compressive longitudinal loading has been validated against three full scale tests on 324 mm nominal diameter, 10.3 mm nominal wall thickness, Grade X52 linepipe. The validation of this method is not as comprehensive as the validation of the method for assessing a single longitudinal corrosion defect subject to internal pressure loading only. The partial safety factors have not been derived from an explicit probabilistic calibration.

The validation of the methods described in this document for the assessment of corrosion defects subject to internal pressure loading plus compressive longitudinal stress (see [3.7.4] and [3.7.5]), is not as comprehensive as the validation of the methods for the assessment of corrosion defects subject to internal pressure loading alone.

The acceptance equation has not been validated for defect dimensions where the breadth (circumferential extent) of the defect exceeds the length of the defect. The partial safety factors for combined loading have not been derived from an explicit probabilistic calibration.

1.13 Definitions

Table 1-1 Definitions of terms

Term	*Definition*
single defect	is one that does not interact with a neighbouring defect. The failure pressure of a single defect is independent of other defects in the pipeline.
interacting defect	is one that interacts with neighbouring defects in an axial or circumferential direction. The failure pressure of an interacting defect is lower than the failure pressure of the individual single defects
complex shaped defect	is a defect that results from combining colonies of interacting defects, or a single defect for which a profile is availabl
pressure, design (p_d	in relation to pipelines, this is the maximum internal pressure during normal operation, referred to the same reference elevation as the incidental pressure (/8/, Sec.1, C304). Also see Figure 1-2
pressure, incidental (p_{inc})	in relation to pipelines, this is the maximum internal pressure the pipeline or pipeline section is designed to withstand during any incidental operating situation, referred to a specified reference elevation (/8/, Sec.1, C306). Also see Figure 1-2
pressure, maximum allowable incidenta	in relation to pipelines, this is the maximum pressure at which the pipeline system shall be operated during incidental (i.e. transient) operation. The maximum allowable incidental pressure is defined as the maximum incidental pressure less the positive tolerance of the Pipeline Safety System (/8/, Sec.1, C309). Also see Figure 1-2
pressure, maximum allowable operating (MAOP)	in relation to pipelines, this is the maximum pressure at which the pipeline system shall be operated during normal operation. The maximum allowable operating pressure is defined as the design pressure less the positive tolerance of the Pipeline Control System (PCS) (/8/, Sec.1, C310). Also see Figure 1-2
pressure, mill test	the test pressure applied to pipe joints and pipe components upon completion of manufacture and fabrication (/8/, Sec.1, C311). Also see Figure 1-2

Term	Definition
pressure, system test	in relation to pipelines, this is the internal pressure applied to the pipeline or pipeline section during testing on completion of installation work to test the pipeline system for tightness (normally performed as hydrostatic testing) (/8/, Sec.1, C314). Also see Figure 1-2

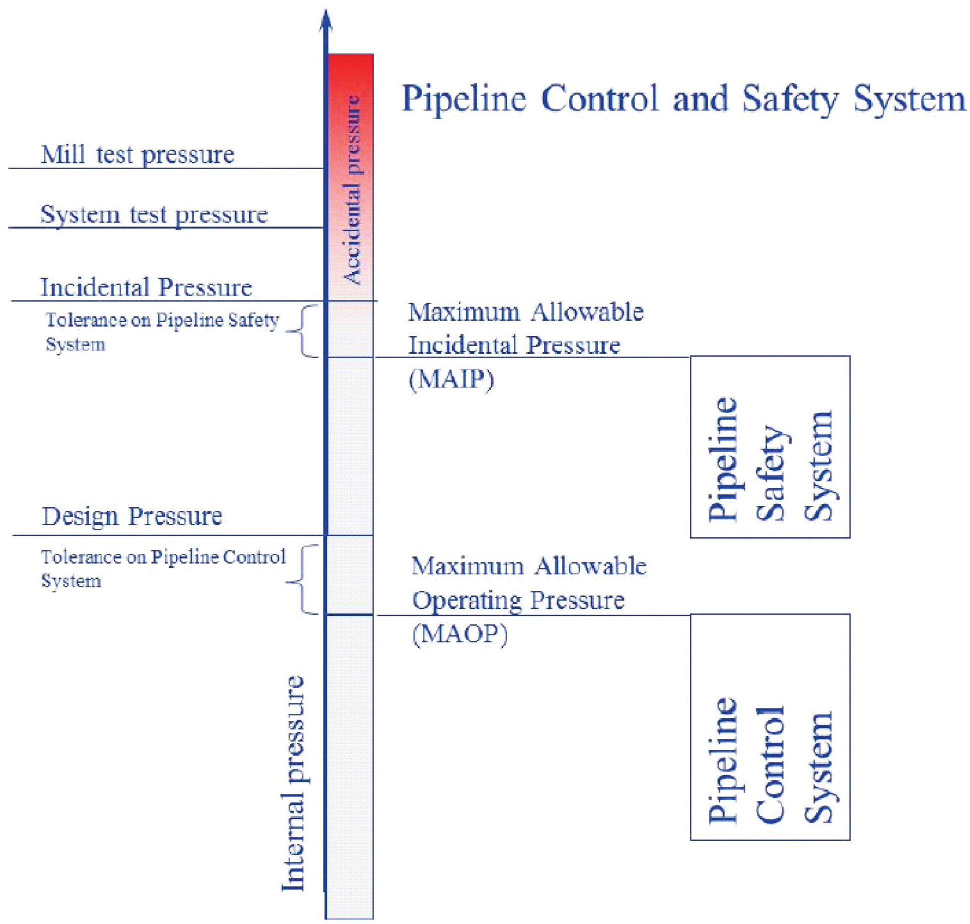

Figure 1-2 Pressure definitions

1.14 Symbols and abbreviations

Symbols - latin characters

A	=	projected area of corrosion in the longitudinal plane through the wall thickness (mm^2)
A_c	=	projected area of corrosion in the circumferential plane through the wall thickness (mm^2)
$A_{i,pit}$	=	area of the ‘i’th idealised pit’in a complex shaped defect (mm^2)
A_{patch}	=	area of an idealised patch in a complex shaped defect (mm^2)
A_r	=	circumferential area reduction factor

	=	$1-A_c/\pi Dt$
	≈	$1-(d/t)\theta$
c	=	circumferential length of corroded region (mm)
$CoV[X]$	=	coefficient of variation of random variable X
	=	StD[X]/E[X]
d	=	depth of corroded region (mm)
d_{ave}	=	average depth of a complex shaped defect (mm)
	=	A/l_{total}
d_{ei}	=	the depth of the 'i'th idealised pit in a pipe with an effectively reduced wall thickness due to a complex corrosion profile (mm)
$d_{e,nm}$	=	verage depth of a defect combined from adjacent pits n to m in a colony of interacting defects in the patch region of a complex corrosion profile (mm)
d_i	=	depth of an individual defect forming part of a colony of interacting defects (mm). Average depth of 'i'th idealised pit in a progressive depth analysis of a complex shaped defect (mm).
d_j	=	the 'j'th depth increment in a progressive depth analysis of a complex shaped defect (mm)
d_{nm}	=	average depth of a defect combined from adjacent defects n to m in a colony of interacting defects (mm)
d_{patch}	=	average depth of an idealised patch in a complex shaped defect (mm)
d_T	=	depth of corroded region after time T (mm)
d_0	=	depth of corroded region at the time of inspection (mm)
$(d/t)_{meas}$	=	measured (relative) defect depth
$(d/t)_{meas,acc}$	=	maximum acceptable measured (relative) defect depth
D	=	nominal outside diameter (mm)
$E[X]$	=	expected value of random variable X
f_u	=	tensile strength to be used in design (N/mm^2)
f_y	=	yield strength to be used in design (N/mm^2)
$f_{u,temp}$	=	de-rating value of f_u
$f_{y,temp}$	=	de-rating value of f_y
F	=	total usage factor
	=	F_1F_2
F_1	=	modelling factor
F_2	=	operational usage factor
F_X	=	external applied longitudinal force (N)
g	=	limit state function
h_{ref}	=	the elevation of the reference point, positive upwards (m)
h_l	=	the elevation of the defect/local pressure point, positive upwards (m)
H_1	=	factor to account for compressive longitudinal stresses

H_2	=	factor to account for tensile longitudinal stresses
I	=	isolated defect number in a colony of N interacting defects
J	=	increment number in a progressive depth analysis of a complex shaped defect
l	=	longitudinal length of corroded region (mm)
l_i	=	longitudinal length of an individual defect forming part of a colony of interacting defects (mm). Longitudinal length of 'i'th idealised pit in a progressive depth analysis of a complex shaped defect (mm).
l_{meas}	=	measured longitudinal length of corroded region (mm)
l_{nm}	=	total longitudinal length of a defect combined from adjacent defects n to m in a colony of interacting defects, including the spacing between them (mm)
l_{total}	=	total longitudinal length of a complex shaped defect (mm)
l_T	=	longitudinal length of corroded region after time T
l_0	=	longitudinal length of corroded region at the time of inspection
M_Y	=	externally applied bending moment (Nmm)
N	=	number of defects in a colony of interacting defects
p_{cap}	=	burst pressure capacity (N/mm^2)
$p_{cap,patch}$	=	capacity pressure of an idealised patch in a complex shaped defect (N/mm^2)
p_{corr}	=	ressure resistance of a single longitudinal corrosion defect under internal pressure loading (N/mm^2)
$p_{corr,circ}$	=	pressure resistance of a single circumferential corrosion defect (N/mm^2)
$p_{corr,comp}$	=	pressure resistance of a single longitudinal corrosion defect under internal pressure and superimposed longitudinal compressive stresses (N/mm^2)
$p_{corr,syst}$	=	pressure resistance including system effect (N/mm^2)
p_d	=	design pressure (N/mm^2)
p_i	=	pressure resistance of individual defects forming a colony of interacting defects (N/mm^2)
p_{inc}	=	incidental pressure (N/mm^2)
p_{le}	=	local external pressure (N/mm^2)
p_{li}	=	local incidental pressure (N/mm^2)
p_{mao}	=	maximum allowable operating pressure (N/mm^2)
p_{nm}	=	pressure resistance of combined adjacent defects n to m, formed from a colony of interacting defects (N/mm^2)
p_{patch}	=	pressure resistance of an idealised patch in a complex shaped defect (N/mm^2)
p_{total}	=	pressure resistance of a complex shaped defect when treated as a single defect (N/mm^2)
P_{comp}	=	failure pressure of the corroded pipe for a single defect subject to internal pressure and compressive longitudinal stresses (N/mm^2)
P_f	=	failure pressure of the corroded pipe (N/mm^2)
P_i	=	failure pressures of an individual defect forming part of a colony of interacting defects (N/mm^2)
P_{INT}	=	annual maximum differential pressure (N/mm^2)

P_{nm}	=	failure pressure of combined adjacent defects n to m, formed from a colony of interacting defects (N/mm^2)
P_{patch}	=	failure pressure of an idealised patch in a complex shaped defect (N/mm^2).
P_{press}	=	failure pressure of the corroded pipe for a single defect subject to internal pressure only (N/mm^2)
P_{sw}	=	safe working pressure of the corroded pipe (N/mm^2)
P_{total}	=	failure pressure of a complex shaped defect when treated as a single defect (N/mm^2)
$Pr()$	=	probability of failure()
Q	=	length correction factor
Q_i	=	length correction factor of an individual defect forming part of a colony of interacting defects.
Q_{nm}	=	length correction factor for a defect combined from adjacent defects n to m in a colony of interacting defects
Q_{total}	=	length correction factor for the total longitudinal length of a complex shaped defect (mm).
R	=	remaining ligament thickness (mm)
r_{corr}	=	estimated corrosion rate (mm/year)
S	=	longitudinal spacing between adjacent defects (mm)
s_i	=	longitudinal spacing between adjacent defects forming part of a colony of interacting defects (mm)
$StD[X]$	=	standard deviation of random variable X.
t	=	uncorroded, measured, pipe wall thickness, or t_{nom} (mm)
t_e	=	equivalent pipe wall thickness used in a progressive depth analysis of a complex shaped defect (mm)
T	=	time (year)
$(X)^*$	=	characteristic value of X
Y_{FEA}	=	model uncertainty given by comparing the predicted capacities to FE analysis
Y_{lab}	=	model uncertainty given by comparing the predicted capacities to laboratory tests
Z	=	circumferential angular spacing between projection lines (degrees)

Symbols – Greek characters

α_{u}	=	material strength factor
ε_{d}	=	factor for defining a fractile value for the corrosion depth
φ	=	circumferential angular spacing between adjacent defects (degrees)
γ_{d}	=	partial safety factor for corrosion depth
γ_{inc}	=	incidental to design pressure ratio, /8/
γ_{m}	=	partial safety factor for longitudinal corrosion model prediction
γ_{mc}	=	partial safety factor for circumferential corrosion model prediction
γ_{s}	=	pressure adjustment factor according to system effect

η	=	partial safety factor for longitudinal stress for circumferential corrosion
θ	=	ratio of circumferential length of corroded region to the nominal outside circumference of the pipe, ($c/\pi D$)
σ_A	=	longitudinal stress due to external applied axial force, based on the nominal wall thickness (N/mm^2)
σ_B	=	longitudinal stress due to external applied bending moment, based on the nominal wall thickness (N/mm^2)
σ_L	=	combined nominal longitudinal stress due to external applied loads (N/mm^2)
$\sigma_{L\text{-nom}}$	=	combined nominal longitudinal stress in the nominal pipe wall due to external applied loads (N/mm^2)
σ_u	=	ultimate tensile strength (N/mm^2).
σ_y	=	ultimate yield strength (N/mm^2).
σ_1	=	lLower bound limit on external applied loads (N/mm^2)
σ_2	=	upper bound limit on external applied loads (N/mm^2)
ξ	=	usage factor for longitudinal stress.

Table 1-2 Abbreviations

Abbreviation	*Description*
API	American Petroleum Institute
ASD	allowable stress design
CMn	carbon manganese
CWT	characteristic wall thickness profile is estabished from RBP giving average over a given section length
LRFD	load and resistance factor design
MAOP	maximum allowable operating pressure
MFL	magnetic flux leakage
MTI	mixed type of interaction
PCS	pressure control system
PoD	probability of detection
PoF	probability of failure
RBP	river bottom profile is the two dimensional representation of the remaining wall thickness along the pipeline length, establilshed fromRWT_{SO} according to methodology in [D.3]
RP	recommende practice
RWT_{SO}	remaining wall thickness data based on *SO* and *WT* data according to methodology in [D.3]
SC	safety class
SMTS	specified minimum tensile strength (N/mm^2)

Abbreviation	*Description*
SMYS	specified minimum yield stress (N/mm^2)
SO	stand-off data (distance from probe to pipe wall - see Figure D-4)
SORM	second order reliability method
ULS	ultimate limit state
UT	ultrasonic technology
UTS	ultimate tensile strength (N/mm^2)
WT	wall thickness data based on the difference between the first and second reflection of the beam from the inspection tool
WTSO	the sum of *SO* and *WT* data (where *WT* data are above a lower cut off value

1.15 Units

The units adopted throughout this document are [N] and [mm], unless otherwise specified.

SECTION 2 METHODOLOGY

2.1 Capacity equation

The expression of the burst capacity for a single longitudinally oriented, rectangular shaped, corrosion defect was developed based on a large number of FE analyses, and a series of full-scale burst tests. By using finite element analyses, the effect of each important parameter was investigated, while the accuracy of the analyses was verified by a large number of full-scale burst tests. The equations used in the development of this recommended practice and in the calibration are fairly complex. For practical use, a simplified capacity equation is given below. For more details see App.E, /15/ and /16/.

The simplified capacity equation of a single rectangular shaped defect is given as:

$$P_{cap} = 1.05 \frac{2t \cdot \sigma_u}{(D-t)} \cdot \frac{(1-(d/t))}{\left(1-\frac{(d/t)}{Q}\right)}$$

where

$$Q = \sqrt{1 + 0.31\left(\frac{l}{\sqrt{Dt}}\right)^2}$$

This capacity equation represents the mean (best) estimate of the capacity of a pipe with a rectangular shaped corrosion (metal loss) defect. This implies that on average, the equation should represent the capacity of the pipe but that some of the defects will fail at a slightly lower pressure, and some at a slightly higher pressure than predicted.

Since the equation is simplified, some effects, and combination of effects, are not represented in detail. This includes e.g. yield to tensile ratio, D/t ratio, and length and depth effect. For example it is known that the equation over-predicts the failure pressure for medium long defect with high yield to tensile ratio (high grade steel), and under-predicts the failure pressure for low yield to tensile ratio (low grade steel).

The accuracy of the capacity equation had to be known for establishing the appropriate safety factors, and the above mentioned effects were accounted for.

The factor 1.05 in the capacity equation is determined from comparison with laboratory test results with rectangular shaped metal loss defects, see /16/.

If the equation is used for irregular or parabolic defect shapes, and the maximum depth and lengths are used, the equation will in general underestimate the failure pressure, as the defect is not as large as the rectangular shaped defect assumed in the capacity equation – see Figure 2-1. This will result in a conservative estimate of the failure pressure capacity for defects shapes other than rectangular.

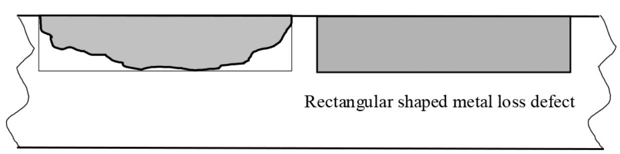

Figure 2-1 Illustration of irregular and rectangular defects

2.2 Sizing accuracy and uncertainties

For known defect size, pipe dimensions and material properties, the capacity equation predicts the burst capacity with a good accuracy. However, these input parameters usually include a certain degree of uncertainty, and this should be accounted for when assessing defects of a corroded pipeline.

A high level of safety (reliability) is required for pipelines. This is obtained by using safety factors in combination with the capacity equation presented in [2.1].

For example, in an assessment of a defect, only the material grade (giving SMTS and SMYS) will usually be available. The actual material properties at the location of the defect will not be known. Furthermore, the defect sizing will be determined with some level of uncertainty. The defect can be shallower, or deeper, than the measured value, as illustrated in Figure 2-2. These uncertainties have to be considered in the defect assessment.

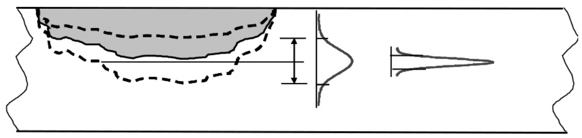

Figure 2-2 Measured defect depth and sizing accuracy

2.3 Part A - calibrated safety factors

The effect of the inspection accuracy, combined with the other uncertainties described above, is accounted for in the calibration of the safety factor. Although a single safety factor to account for these uncertainties would give simpler calculations, several partial safety factors were introduced to give results with a consistent reliability level for the validity range of input parameters. If a single safety factor should cover the full range of input parameters, this would give results with a varying reliability level depending on the input parameters. If the safety factor should be selected such that the minimum required reliability level is satisfied in all cases, the code would be undesirably conservative for some combinations of the input parameters.

Results of FE analyses and laboratory tests, together with statistical data of material properties, pressure variations and selected levels of uncertainties in the defect sizing, form the required basis for a reliability code calibration where appropriate safety factors were defined.

For the part A approach presented in Sec.3, the assessment of a pipeline with a corrosion defect is done with an acceptance equation based on the capacity equation given in [2.1] including these defined safety factors. The safety factors are described in Sec.3.

2.4 Part B - allowable stress approach

The approach given in part B is based on the allowable stress design format. The failure pressure of the pipeline with the corrosion defect is calculated, and multiplied by a usage factor. Often the original design factor is applied as the usage factor.

When assessing corrosion defects, due consideration should be given to the measurement uncertainty of the defect dimensions and the pipeline geometry. In contrast to part A, these uncertainties are not explicitly included in the part B approach, and are left to the user to consider and account for in the assessment.

2.5 Onshore pipelines

Design codes for onshore pipelines allow, in general, a lower utilisation of the material compared to offshore codes, i.e. the safety factors are higher. It is assumed that these factors implicitly cover other loads and degradation mechanisms than considered in this recommended practice, and if using part A this could be in conflict with the safety philosophy in the original design code. part B could be more appropriate for onshore pipelines, where the user have to account for these additional failures aspects. However, when using Part B, it is recommended that the user also check according to part A. If this yields stricter results, considerations should be made.

2.6 Characteristic material properties

The tensile strength (f_u) is used in the acceptance equation. SMTS is given in the linepipe steel material specification (e.g. API 5L, /14/ and DNV-ST-F101 Sec.13 /8/) for each material grade. The characteristic material properties shall be used in the assessment of the metal loss defects – see Table 2-1. The material grades refer to mechanical properties at room temperature, and possible temperature effects on the material properties shall also be considered. Local design temperature (at defect location) could also be considered.

Table 2-1 Characteristic material properties

$f_y = \left(SMYS - f_{y,temp}\right) \cdot \alpha_u$
$f_u = \left(SMTS - f_{u,\,temp}\right) \cdot \alpha_u$

where

$f_{y,temp}$ and $f_{u,temp}$ are the de-rating value of the yield stress and tensile strength due to temperature and α_u is the material strength factor.

The material factor, α_u, depends on Supplementary requirement U as defined in DNV-ST-F101, see Table 2-2.

Table 2-2 Material strength factor, α_U

Factor	*Normally*	*Supplementary requirement fulfilled*
α_U	0.96	1.00

Guidance note:

For pipelines which are not designed according DNV-ST-F101:

- the α_u factor are to be taken as 0.96 when performing a part A assessment
- the α_u factor could be considered included in the usage/design factor when carrying out a part B assessment.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

The temperature de-rating is highly material dependent and should preferably be based on detailed knowledge of the actual material. In lack of any material information, the values in Figure 2-3 should be used for both yield stress and tensile strength for temperatures above 50°C.

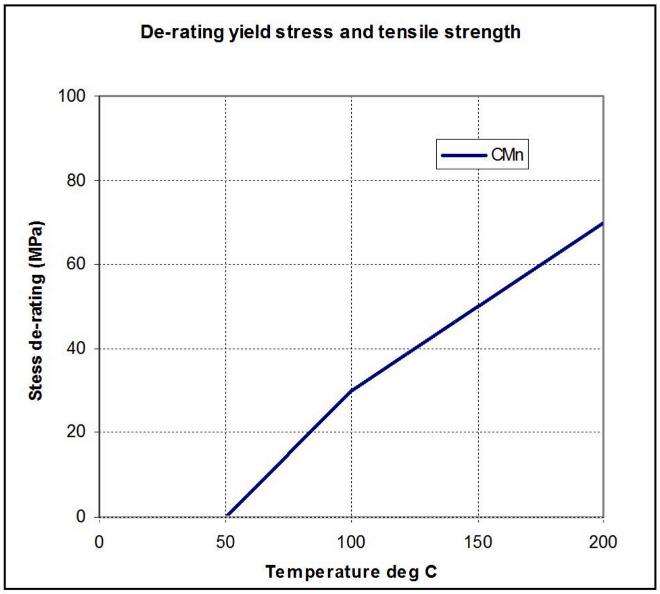

Figure 2-3 Proposed de-rating values for carbon steel

2.7 Pressure reference height and static head

The assessment of corrosion defects should consider the pressure load at the location of the defect, both internal and external. The pressure reference height and the elevation of the defect shall be known.

For offshore pipelines the benefit of external water pressure should be utilised, and the increased pressure due to the internal static head has to be included.

For onshore pipelines only the internal static head shall be included.

2.8 Probabilistic assessments

The safety factors in this recommended practice are derived from probabilistic calibrations, and based on a set of input parameter distributions that are considered to be representative.

When more accurate knowledge of the distributions is known, or if further growth of the metal loss defects is to be included, probabilistic calculations can provide a strong tool for the assessment of metal loss defects.

Probabilistic assessments of pipes with metal loss defects can be based on the following limit state function:

$g = P_{cap} - P_{INT}$

where

P_{cap} = the burst pressure capacity as defined in App.E.

P_{INT} = the annual maximum differential pressure.

The probability of pipeline burst is given as $Pr(g < 0)$. In a probabilistic assessment the failure probability should be defined as the probability of pipeline burst or leakage, where the probability of leakage is the probability that a measured defect has a depth larger than the pipe wall thickness, $Pr(d/t \geq 1)$.

The parameters in the limit state should be modelled with their actual distributions, and considerations should be given to the inspection sizing accuracy. If such distributions are not available, it is possible to apply the set of input parameter distributions which were used in the calibration of the safety factors included in this recommended practice. These are presented in Table 2-3 and are considered to be representative for pipelines.

The significance of each parameter varies, and some may be used as a fixed value, rather than a variable with associated distribution. However, the distributions in the model and the sizing accuracy have to be included in a probabilistic assessment, where it is often seen that only one of these is accounted for. The uncertainty in the sizing accuracy is given in Sec.3 of this recommended practice.

In addition to the inspection accuracy, the corrosion rate will also add to the uncertainty of the future defect size (also see [2.9]).

Table 2-3 Parameters in the modelling of the burst limit state equation

Variable	*Distribution*	*Mean*	*CoV*	*Guidance notes for pipeline specific probabilistic calculations*
P_{INT}	Gumbel	$1.05 \cdot p_d$	3.0%	
D	Deterministic	Nominal	-	The outer diameter is assumed fixed.
t	Normal	Nominal	3.0%	For absolute measurement inspections the measured pipe wall thickness around a corroded area can be assumed to be at least as accurate as the corrosion depth measurement.
σ_y	Normal	1.08 SMYS	4.0% 8.0%	The uncertainty in the material properties depends on the material quality level. The lower CoV values can be used when the supplementary requirement U is fulfilled.
σ_u	Normal	1.09 SMTS	3.0% 6.0%	
l_{meas}	Normal	Measured value	Specified	The standard deviation in the length measurement can be assumed less than 20 times the standard deviation in the depth measurement i.e. $StD[l_{meas}] < 20 \bullet StD[d/t]$.
d/t	Normal	Measured value	Specified	
Y_{FEA}	Normal	1.0	2.0%	Model uncertainty valid for the burst pressure capacity defined in App.E.
Y_{lab}	Normal	1.0	8.0%	

2.9 Corrosion development

2.9.1 General guidance on corrosion rate estimation

In corrosion rate estimations, monitoring/inspection data, operational trends, change in operational conditions, historical events/incidents and experience should be considered. If corrosion models alone are used for corrosion estimation, one needs to be aware of their limits and relevance with regard to the field conditions. A coarse work process is illustrated in Figure 2-4 and a corrosion specialist should be involved in the corrosion rate estimation.

When inspections are input to estimation of corrosion growth and corrosion rates, one needs to among others be aware of the following:

— time between inspections:

  — The corrosion rate will normally not be constant between two inspections. If there have been significant changes in the operation, or special incidents/events during the period in question, this shall be taken into account when estimating the corrosion rate. This is especially important for long inspection intervals.

  — For short inspection intervals, the rate may be dominated by measuring uncertainties alone.

— accuracy of the inspection tool and uncertainties in measurements

— quality of the inspections
— bias between inspections (e.g. due to software/algorithms used for processing inspection data)
— reporting threshold for the feature list with regard to depth (not applicable for detailed UT data)
— sizing of defects; defects in feature lists are reported as single defects with a depth equal to the deepest point reported. The reported depth is normally not representative for the entire length of the defect (unless detailed UT data have been provided).

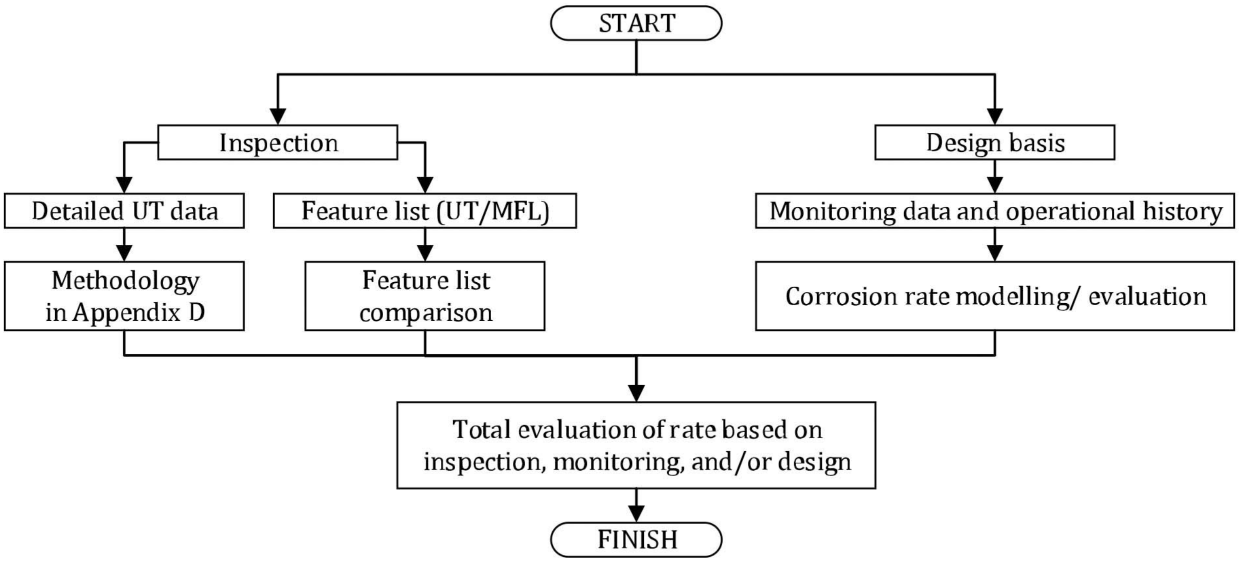

Figure 2-4 Work process for corrosion rate estimation

2.9.2 Remaining life estimation

Given a corrosion rate and associated uncertainty, various approaches for remaining life estimations can be utilized. The remaining life of a pipeline with regard to the burst limit state is considered to be the time from the last inspection to the time when the pressure containment capacity reaches the acceptance criteria – see [3.7.3]. Either the best estimate or a conservative/upper bound corrosion rate can be used as input to the assessment, depending on the method used. If the corrosion rate is based on previous inspection data, it can only be used for similar operating conditions and when no significant change in the corrosivity is expected. Otherwise, additional considerations need to be taken into account as discussed in [2.9.1] in order to find the best estimate of the future corrosion rate.

For a given corrosion rate the defect size growth can be estimated in various manners. The mean defect depth can be calculated according to the following equation:

$$d_T = d_0 + T \cdot r_{corr}$$

The mean defect length development can be estimated either based on a separate corrosion rate for the length direction or by assuming proportional growth with the depth.

$$l_T = l_0 + t \cdot r_{corr,\ length}$$

or

$$l_T = l_0 \cdot \left(l + \frac{T \cdot r_{corr}}{d_0} \right)$$

where:

d_T	- defect depth after time T
l_T	- defect length after time T
l_0	- defect length at the time of the inspection
d_0	- defect depth at the time of the inspection
r_{corr}	- estimated corrosion rate

Four alternative methods to estimate the remaining life are presented in this recommended practice:

1) Deterministic approach – Increasing defect size for each year to come based on engineering judgement of a potential corrosion rate and comparison with code requirement, see [2.9.2.1].
2) Deterministic approach with associated uncertainties/semi-probabilistic approach – Estimation of corrosion rate and uncertainties, see [2.9.2.2].
3) Probabilistic approach – Use of probabilistic methods, see [2.9.2.3].
4) Methodology for corrosion rate and remaining life estimation based on detailed UT data, see App.D.

2.9.2.1 Deterministic approach

The remaining life with regard to burst limit state is the time until a defect reaches the acceptable measured defect depth curve as illustrated in Figure 2-5. The growth of the defects should be based on a conservative/upper bound corrosion rate as this method does not take into account uncertainties in future corrosion rate. For a chosen section, the upper 95% quantile rate can be used and is calculated as μ + 1.645σ, where μ and σ are the average corrosion rate and the standard deviation respectively. Engineering judgment shall be applied when defining the section. Section selection should be conservative, i.e. care should be taken with regard to inclusion of parts with low corrosion rates.

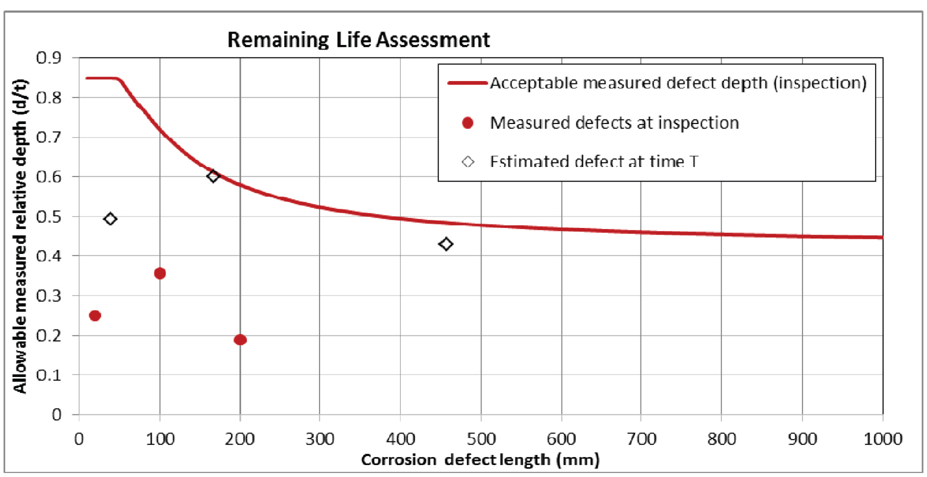

Figure 2-5 Remaining life assessment based on a deterministic approach

2.9.2.2 Deterministic approach with associated uncertainties/semi-probabilistic approach

A defect is measured with an uncertainty (inspection accuracy). When future corrosion development is assessed, the corrosion rate is uncertain. Hence the estimated defect size in T years has both an increased mean value and an increased uncertainty. By describing the corrosion rate by a mean value and a standard deviation, the uncertainty in the corrosion rate will be accounted for in the same manner as measuring uncertainty is in part A. Hence, over time the allowable defect size curve will decrease, while the estimated defect length and depth will increase as illustrated in Figure 2-6. The remaining life is the time until the first defect reaches the allowable defect size curve.

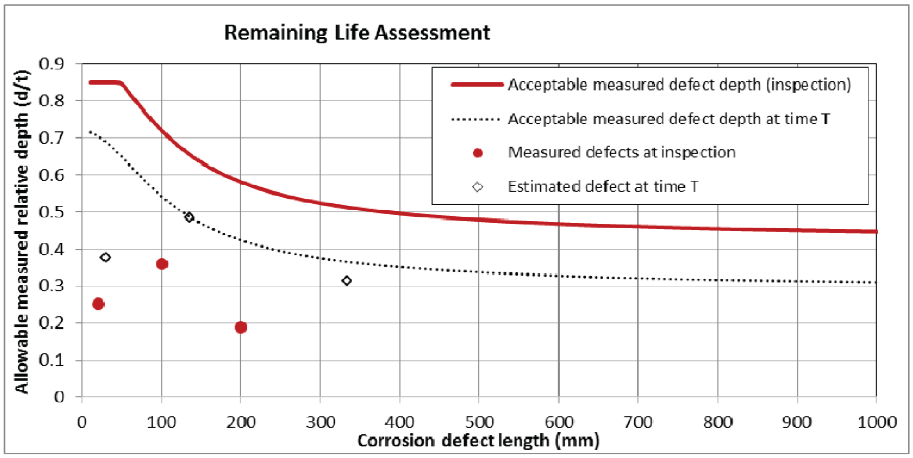

Figure 2-6 Remaining life assessment based on a semi-probabilistic approach

The uncertainty in the corrosion rate can be estimated as follows (given as standard deviation):

$$StD[d/t]_T \approx \sqrt{StD\left[(d/t)_0\right]^2 + \frac{T^2}{t^2} \cdot StD\left[r_{corr}\right]^2}$$

$$\left(\bar{d}/t\right)_T \approx (d/t)_0 + T \cdot \left(\bar{r}_{corr}/t\right)$$

The maximum acceptable defect curves after time T will be produced by combining the equations above with the equations in [3.7.3.2]. When estimating the growth of the defects, a best estimate of the corrosion rate should be used in this method, as the method itself accounts for uncertainties in the corrosion rate.

2.9.2.3 Probabilistic approach

Assuming that a corrosion rate (distribution) has been established, the probability of failure as a function of time can be defined by introducing the estimated future defect into the limit state equation (see [2.8]). The probabilistic model obtained in this fashion can then be utilised to determine the time before the probability of failure exceeds the annual target failure probability. These defined targets are presented in Table 3-1. Care needs to therefore be taken to obtain annual failure probabilities and not (only) accumulated failure probabilities for time periods exposed to the assumed corrosion rates.

The failure probability is the probability that a pipeline will either leak or burst:

— The leak limit state is defined as the difference between the wall thickness and the defect depth. The probability of leakage is defined as the probability that a measured defect has a depth larger than the pipe wall thickness. The (nominal) wall thickness is assumed time invariant while the pipeline (defect) is degrading as a function of time. The failure probability that is derived for a defect exposed to the assumed corrosion rate for a certain time period is an accumulated probability of failure for the time period in question. It is the probability that the pipeline will leak within the time period considered.
— The burst limit state is defined as the difference between the corroded pipe capacity and the annual largest internal pressure. For a degrading pipeline, both the capacity and loading is varying over time, making the formulation of a time variant failure probability significantly more complex, see /20/. For simplification, it can be conservatively assumed that any stage of the time dependant capacity will be

exposed to the annual largest loading. This assumption is adopted by viewing the (annual largest) internal pressure as time invariant. In this sense, introducing a future defect to represent the measured defect after some time T will provide the probability of burst as an accumulated failure probability. That is, the probability of burst in the time period prior to T.

Annual probabilities of failure can be found as a function of the accumulated failure probabilities of two subsequent time periods (where one period is the prior period + 1 year) - see guidance note below.

Guidance note:

The lifetime distribution - The lifetime of a pipeline with respect to the above failure modes is defined as the time until failure occurs. The lifetime distribution and time variant failure probability are connected through the equality

$$P(L < T) = P(Failure\ \ in\ \ the\ \ time\ period\ t \in [0, T]) = P(g(t) < 0)$$

where L denotes the lifetime and $g(t)$ is the time dependant limit state function. Time-limited failure probabilities can be obtained from the accumulated failure probability as

$$\begin{aligned} P\left(T_{start} < L < T_{end}\right) &= P\left(Failure\ \ in\ \ the\ \ time\ \ period\ \ t \in \left[T_{start}, T_{end}\right]\right) \\ &= P\left(Failure\ \ before\ \ time\ \ t =\ T_{end}\right) - P\left(Failure\ before time\ \ \ t = T_{start}\right) \end{aligned}$$

or equivalently

$$P\left(T_{start} < L < T_{end}\right) = P\left(L < T_{end}\right) - P\left(L < T_{start}\right)$$

For practical purposes the annual failure probabilities are often of interest. This can be the time-limited annual failure probability

$$P(T < L < T + 1) = P(L < T + 1) - P(L < T)$$

,

or the probability of failure in the time period [T, $T+1$] given that no failure has occurred before the time T. This conditional probability is given as

$$P\left(L \in \left[T, T + 1\right] \middle| L > T\right) = 1 - \frac{1 - P(L < T + 1)}{1 - P(L < T)}$$

which coincides with the failure rate in the time period [T, $T+1$].

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SECTION 3 PART A - CALIBRATED SAFETY FACTOR APPROACH

3.1 Introduction

The approach given in part A includes calibrated safety factors. Uncertainties associated with the sizing of the defect depth and the material properties are specifically considered. Probabilistically calibrated equations for the assessment of a corroded pipeline are given (in [3.7] to [3.9]). These equations are based on the LRFD (load and resistance factor design) methodology.

In this section, partial safety factors are given for two general inspection methods (based on relative measurements e.g. magnetic flux leakage (MFL), and based on absolute measurements e.g. ultrasonic (UT)), four different levels of inspection accuracy, and four different reliability levels.

3.2 Reliability levels

Pipeline design is normally to be based on safety/location class, fluid category and potential failure consequence for each failure mode, and to be classified into safety classes, see Table 3-1.

Table 3-1 Safety Class and target annual failure probability for ultimate limit state (ULS)

Safety class	*Indicating a target annual failure probability of:*
Very high	$< 10^{-6}$
High	$< 10^{-5}$
Medium	$< 10^{-4}$
Low	$< 10^{-3}$

Subsea oil and gas pipelines, where no frequent human activity is anticipated, will normally be classified as safety class medium. Safety class very high is used for the parts of pipelines close to shore and/or onshore sections with frequent human activity (suburban housing developments, residential areas, industrial areas and other populated areas). Safety class high is used for risers and the parts of the pipeline close to platforms, or in areas with frequent human activity. Safety class low can be considered for e.g. water injection pipelines where a potential failure only relates to economic consequences (i.e. no environmental and safety consequences). For more details, see DNV-ST-F101 /8/ and other relevant pipeline codes.

3.3 Partial safety factors and fractile values

The partial safety factors are given as functions of the sizing accuracy of the measured defect depth for inspections based on relative depth measurements and for inspections based on absolute depth. For inspections based on relative depth measurements the accuracy is normally quoted as a fraction of the wall thickness. For inspections based on absolute depth measurements the accuracy is normally quoted directly. An appropriate sizing accuracy should be selected in consultation with the inspection tool provider.

The acceptance equation is based on two partial safety factors and corresponding fractile levels for the characteristic values.

γ_m	=	partial safety factor for model prediction.
γ_d	=	partial safety factor for corrosion depth.
ε_d	=	factor for defining a fractile value for the corrosion depth.
StD[d/t]	=	standard deviation of the measured (d/t) ratio (based on the specification of the tool).

The safety factors are determined based on:

- safety class (or equivalent), usually from design
- inspection method, relative or absolute
- inspection accuracy and confidence level.

Safety factor γ_m is given in Table 3-2 for inspection results based on relative depth measurements, (e.g. MFL measurements), and for absolute depth measurements (e.g. UT measurements). MFL is a relative measurement where the defect depth measurement and the accuracy are given as a fraction of the wall thickness. The UT is an absolute measurement where the local wall thickness, the defect depth measurement and the accuracy are given directly.

Table 3-2 Partial safety factor γ_m

Inspection method	*Safety class*			
	Low	*Medium*	*High*	*Very High*
Relative (e.g. MFL)	γ_m = 0.90	γ_m = 0.85	γ_m = 0.80	γ_m = 0.76
Absolute (e.g. UT)	γ_m = 0.94	γ_m = 0.88	γ_m = 0.82	γ_m = 0.77
Note: in order to achieve a better harmonization with DNV-ST-F101, is now based on the incidental pressure - see Figure 1-2/[1.13]. The supplementary material requirement has also been removed from the safety factor and introduced in the tensile strength in the acceptance equation - see Table 2-1. The factors from the 2010 revision have therefore been multiplied by 1.1 and divided by 0.96. This does not imply any changes in the allowable utilization.				

The factors for absolute measurement are higher since it is assumed that the pipe wall thickness around the corroded area is measured with at least the same accuracy as the corrosion depth. The measured values of the wall thickness (t) should be used in the calculation of the allowable pressure.

From the inspection accuracy and confidence level, the standard deviation in the sizing accuracy can be determined. The standard deviation is further used to determine the γ_d safety factor and the ε_d fractile value.

The approach to calculate the standard deviation StD[d/t], where a Normal distribution is assumed, is:

StD[d/t] for relative (e.g. MFL):

StD[d/t] $= acc\_rel/\Phi^{-1}(0.5+conf/2)$

acc_rel = the relative depth accuracy, e.g. 0.2 (0.2 t)

conf = the confidence level, e.g. 0.8 (80%)

Φ^{-1} = the inverse of the cumulative distribution function of a standard normal variable*

*The Microsoft Excel function NORMSINV(x) (in newer versions: NORM.S.INV) returns the inverse of the standard normal cumulative distribution at probability x.

The confidence level indicates the portion of the measurements that will fall within the given sizing accuracy. A selected set of calculated standard deviations for relative sizing accuracy is given in Table 3-3.

Table 3-3 Standard deviation and confidence level

Relative sizing accuracy	*Confidence level*	
	80% (0.80)	*90% (0.90)*
Exact ± (0. 0 of t)	StD[d/t] = 0.00	StD[d/t] = 0.00
± 0.05 of t	StD[d/t] = 0.04	StD[d/t] = 0.03
± 0.10 of t	StD[d/t] = 0.08	StD[d/t] = 0.06
± 0.20 of t	StD[d/t] = 0.16	StD[d/t] = 0.12

Figure 3-1 illustrates a sizing accuracy of ± 5% of t, quoted with a confidence level of 80%. A Normal distribution is assumed.

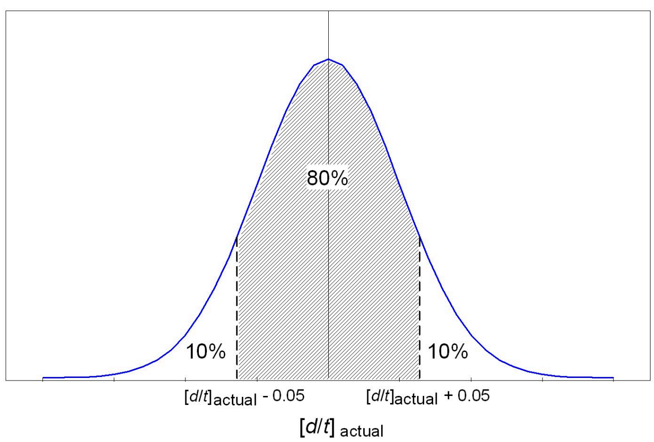


Figure 3-1 Example of a sizing accuracy of ± 5% of t, quoted with a confidence level of 80%

StD[d/t] for absolute (e.g. UT):

StD[d/t] = $$\sqrt{2}acc\_abs/\left(t\cdot\varphi^{-1}\left(0.5+conf/2\right)\right)$$

acc_abs = the absolute depth accuracy, e.g. 0.5 (0.5 mm)

conf = the confidence level, e.g. 0.8 (80%)

Φ^{-1}= the inverse of the cumulative distribution function of a standard normal variable*

*The Microsoft Excel function NORMSINV(x) (in newer versions: NORM.S.INV) returns the inverse of the standard normal cumulative distribution at probability x.

Note that the expression is dependent on the wall thickness. This function is a slightly conservative approximation of the detailed expressions of the standard deviations, see App.C, of absolute measurements used in the 1999 version of this recommended practice. The detailed expressions may also be used. The simplification conservatively assumes d = t in the calculation of StD[d/t]. A selected set of calculated standard deviations for absolute sizing accuracy is given in Table 3-4 through to Table 3-6 for a wall thickness of 6.35 mm, 12.7 mm and 19.05 mm.

Table 3-4 Standard deviation and confidence level, t = 6.35 mm

Absolute sizing accuracy	*Confidence level*	
	80% (0.80)	*90% (0.90)*
Exact ± (0 mm)	StD[d/t] = 0.000	StD[d/t] = 0.000
± 0.25 mm	StD[d/t] = 0.043	StD[d/t] = 0.034
± 0.5 mm	StD[d/t] = 0.087	StD[d/t] = 0.068
± 1.0 mm	StD[d/t] = 0.174	StD[d/t] = 0.135

Table 3-5 Standard deviation and confidence level, t = 12.7 mm

Absolute sizing accuracy	*Confidence level*	
	80% (0.80)	*90% (0.90)*
Exact ± (0 mm)	StD[d/t] = 0.000	StD[d/t] = 0.000
± 0.25 mm	StD[d/t] = 0.022	StD[d/t] = 0.017
± 0.5 mm	StD[d/t] = 0.043	StD[d/t] = 0.034
± 1.0 mm	StD[d/t] = 0.087	StD[d/t] = 0.068

Table 3-6 Standard deviation and confidence level, t =19.05 mm

Absolute sizing accuracy	*Confidence level*	
	80% (0.80)	*90% (0.90)*
Exact ± (0 mm)	StD[d/t] = 0.000	StD[d/t] = 0.000
± 0.25 mm	StD[d/t] = 0.014	StD[d/t] = 0.011
± 0.5 mm	StD[d/t] = 0.029	StD[d/t] = 0.023
± 1.0 mm	StD[d/t] = 0.058	StD[d/t] = 0.045

Safety factor γ_d and fractile value ε_d:

The γ_d safety factor and the ε_d fractile values are given in Table 3-7 for various levels of inspection accuracy (defined in terms of the standard deviation) and Safety Class:

Table 3-7 Partial safety factor and fractile value

Inspection sizing accuracy, StD[d/t]	ε_d	*Safety class*			
		Low	*Medium*	*High*	*Very High*
(exact) 0.00	0.0	γ_d = 1.00	γ_d = 1.00	γ_d = 1.00	γ_d = 1.00
0.04	0.0	γ_d = 1.16	γ_d = 1.16	γ_d = 1.16	γ_d = 1.19
0.08	1.0	γ_d = 1.20	γ_d = 1.28	γ_d = 1.32	γ_d = 1.43
0.16	2.0	γ_d = 1.20	γ_d = 1.38	γ_d = 1.58	γ_d = 1.84

Polynomial equations can be used to determine the appropriate partial safety factors and fractile values for intermediate values of StD[d/t] and are given in Table 3-8. The polynomial equations are curve fits based on the calibrated factors given in Table 3-7. The curves are also shown in Figure 3-2 and Figure 3-3.

In the determination of the partial safety factors it is assumed that the standard deviation in the length measurement is less than 20 times the standard deviation in the depth measurement.

Table 3-8 Polynomial equations for partial safety factor and fractile value, see Table 3-7. Substitute "a" with "StD[d/t]"

Safety class	γ_d *and* ε_d	*Range*
Low	$\gamma_d = 1.0 + 4.0\ a$	$a < 0.04$
	$\gamma_d = 1.0 + 5.5\ a - 37.5\ a^2$	$0.04 \le a < 0.08$
	$\gamma_d = 1.2$	$0.08 \le a \le 0.16$
Medium	$\gamma_d = 1.0 + 4.6\ a - 13.9\ a^2$	$a \le 0.16$
High	$\gamma_d = 1.0 + 4.3\ a - 4.1\ a^2$	$a \le 0.16$
Very High	$\gamma_d = 1.0 + 4.0\ a$	$a < 0.03$
	$\gamma_d = 0.92 + 7.1\ a - 8.3\ a^2$	$0.03 \le a < 0.16$
(all)	$\varepsilon_d = 0$ $\varepsilon_d = -1.33 + 37.5\ a - 104.2\ a^2$	$a \le 0.04$ $0.04 < a \le 0.16$

The variation of the partial safety factors γ_d and ε_d with StD[d/t] are shown in Figure 3-2 and Figure 3-3.

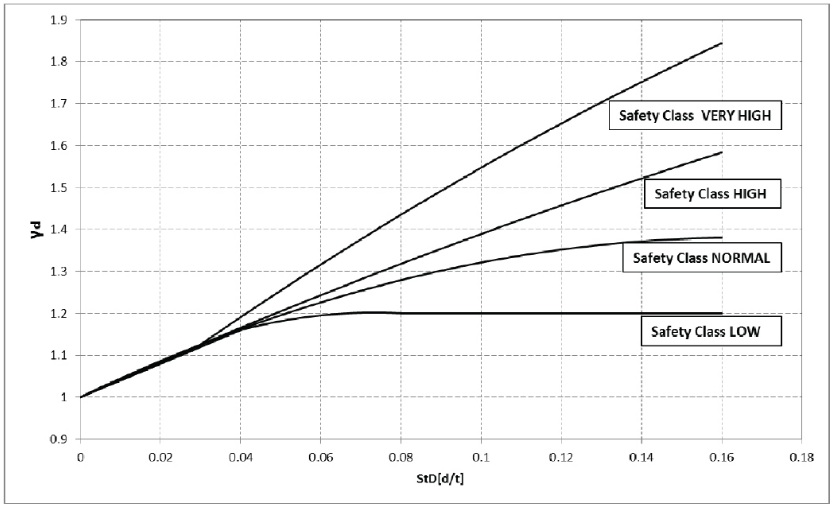


Figure 3-2 Partial safety factor γ_d with StD[d/t]

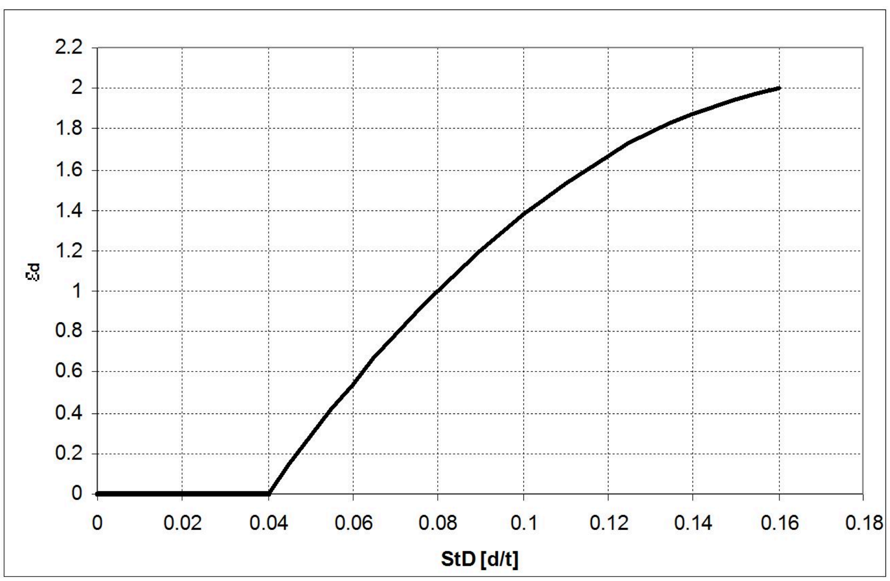


Figure 3-3 Safety factor ε_d with StD[d/t]

3.4 Circumferential corrosion

Partial safety factors factor γ_{mc} and η are given in Table 3-9 for a single circumferential corrosion defect under internal pressure and longitudinal compressive stresses.

Table 3-9 Partial safety factors γ_{mc} and η

Safety class	*Factor γ_{mc}*	*Factor η*
Low	γ_{mc} = 0.94	η = 1.00
Medium	γ_{mc} = 0.88	η = 0.90
High	γ_{mc} = 0.82	η = 0.80
Very High	γ_{mc} = 0.77	η = 0.70

The calibration of the partial safety factors for a single circumferential corrosion defect under internal pressure and longitudinal compressive stresses did not consider the inspection accuracy.

3.5 Usage factors for longitudinal stress

The usage factors for longitudinal stress are given in Table 3-10.

Table 3-10 Usage factors ξ

Safety class	*Usage factor ξ*
Low	ξ = 0.90
Medium	ξ = 0.85
High	ξ = 0.80
Very high	ξ = 0.75

3.6 System effect

The target reliability levels for assessments of metal loss defects are defined in [3.1]- [3.5]. If the defect in question is clearly the most severe defect governing the pressure resistance (p_{corr}), then this defect will also govern the reliability level of the pipeline for failure due to corrosion. In the case of several corrosion defects, each with approximately the same pressure resistance, the system effect shall be accounted for when determining the reliability level of the pipeline (also see DNV-ST-F101 /8/ for more on system effects). Adding the failure probability of each defect will conservatively assess the system effect.

A method for determining pressure resistance including system effect is given in App.D as a part of the method for assessing a corroded pipeline based on detailed UT inspection data. A simplified method that does not require detailed inspection data is presented in this section. The pressure resistance for a pipeline including system effect ($p_{corr,syst}$), is estimated by adjusting the pressure resistance of the most severe defect by a pressure resistance factor found from Figure 3-4*, where the relation between the pressure resistance factor and number of corroded sections is given.

Note:

* Figure 3-4 is based on probabilistic modelling of the limit state and the pressure resistance factor, γ_S, by use of the analytical method SORM (second order reliability method) including the uncertainty in parameters as given in Table 2-3. In the procedure used to establish the figure, the first step was to find the load adjustment factor that leads to an acceptable probability of failure given a resistance adjustment factor of unity. The resistance is then modelled as the minimum resistance of N defects/sections and adjustments to the factored resistance were made in order to achieve the acceptable probability of failure. By this procedure, the factored resistance was estimated for N = 1, 10, …,100 000 sections. Due to the distributions of the stochastic parameters (as given in Table 2-3) the minimum resistance decreases when N increases.

---e-n-d---o-f---n-o-t-e---

A section can typically be 1-10 m. In pipelines with severe corrosion, the length of the defects is often reported to be equal to the joint length and number of defects can be counted instead of number of corroded sections. For a long pipeline (100.000 sections) that experiences uniform corrosion along its entire length, the system effect may reduce the resistance of the pipe by approximately 20%.

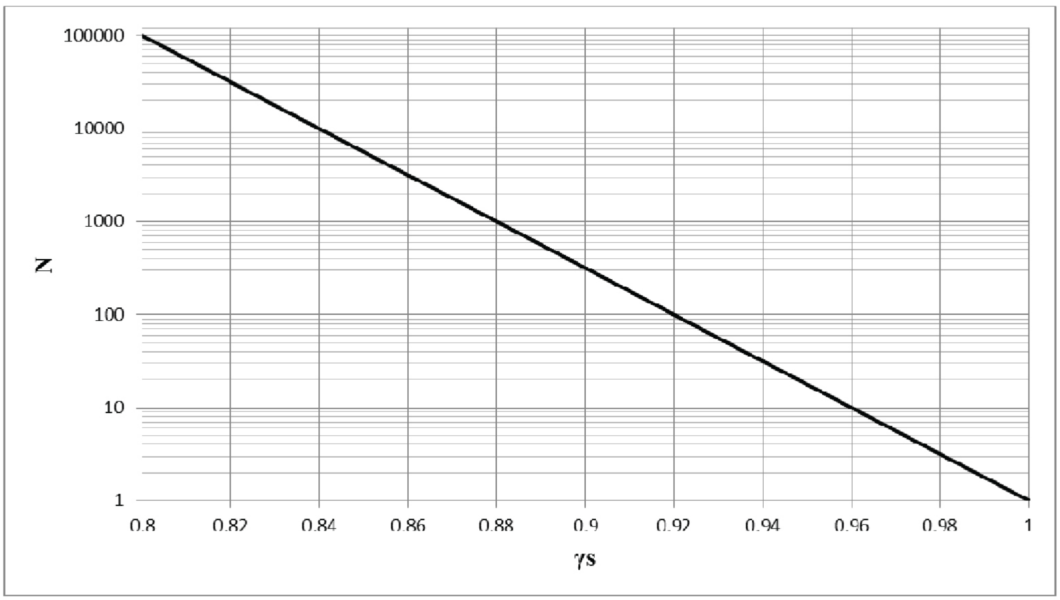


Figure 3-4 Relation between the number of corroded sections N and γ_s

The pressure resistance including system effect can be estimated using the following procedure:

STEP 1 Calculate the pressure resistance for each defect or corroded section as a single defect. p_{corr} will be the pressure resistance for the most severe defect.

STEP 2 Present the pressure resistance for all the selected defects/sections in a histogram with pressure on the horizontal axis and number of defects/sections on the vertical axis.

STEP 3 Define a pressure limit, p = 1.20 p_{corr}. The defects/sections below p_{lim} are the defects/sections that will contribute to the system effect.

STEP 4 Count the number of defects with capacity less than p and find the pressure resistance reduction factor from Figure 3-4.

STEP 5 Calculate pressure resistance including system effect:

$$p_{corr,\ syst} = \gamma_s \cdot p_{corr}$$

STEP 6 If the pressure resistance including system effect is unacceptable or it is $_{lim}$considered to be too conservative, more detailed calculation for determination of pressure resistance including system effect can be carried out according to the methodology given in App.D.

3.7 Assessment of a single defect

3.7.1 Requirements

Isolated metal loss defects shall be individually assessed as single defects, see Figure 3-5. Single defects where the length exceeds the breadth (circumferential extent) are considered to be longitudinal defects and are covered by [3.7.3] and [3.7.4].

For (single) circumferential defects, where the defect breadth exceeds the length, [3.7.5] applies. However, it is required to also assess according to [3.7.3] and [3.7.4] as well.

Adjacent defects can interact to lead to a pressure resistance that is lower than the individual pressure resistances of the isolated defects treated as single defects. For the case where interaction occurs (longitudinal and/or circumferential), the single defect equation is no longer valid and the procedure given in [3.8] shall be applied. Figure 3-6 shows the key dimensions for defect interaction.

A defect can be treated as an isolated defect, and interaction with other defects need not be considered, if either of the following conditions is satisfied:

1) The circumferential angular spacing between adjacent defects, φ (degrees):

$$\phi > 360\sqrt{\frac{t}{D}}$$

2) Or, the axial spacing between adjacent defects, s:

$$s > 2\sqrt{Dt}$$

3.7.2 Acceptance criteria

3.7.2.1 General

The following requirements with regard to defect depth shall be fulfilled:

Measured defects depths shall not exceed 85% if the wall thickness, i.e. minimum remaining wall thickness ≥15% of the (nominal) wall thickness.

The measured defect depth plus the uncertainty in the defect sizing cannot exceed the wall thickness, with the reliability level applicable for the defect, identified by the safety or location class.

If the wall thickness is close to the required minimum remaining wall thickness (e.g. for a 10 mm wall thickness pipeline the minimum requirement may be only 1.5 mm), special attention should be given to these defects; in terms of defect sizing uncertainty, potential further growth and consequences of a leak.

3.7.2.2 Burst limit state – corroded pipe

The pressure containment shall fulfil the following criterion

$$p_{li} - p_{le} \leq p_{corr} \text{ , } p_{le} = -\rho_{sw} \cdot g \cdot h_l$$

The above criterion considers local differential pressure and shall be fulfilled at all locations. The local pressure is the internal pressure at a specified point based on the reference pressure adjusted for the fluid column weight due to the difference in elevation. It can be expressed as

$$p_{li} = p_{inc} + \rho_{cont} \cdot g \cdot \left(h_{ref} - h_l\right)$$

$$p_{inc} = p_d \cdot \gamma_{inc}$$

Where

p_{li}	=	local incidental pressure
p_{inc}	=	incidental pressure
p_{le}	=	local external pressure
p_{corr}	=	pressure resistance
g	=	gravity
h_{ref}	=	the elevation of the reference point (positive upwards/typically in relation to sea level)
h_l	=	the elevation of the defect/local pressure point (positive upwards/ typically in relation to sea level)
ρ_{sw}	=	density of seawater
ρ_{cont}	=	the density of the relevant content of the pipeline
γ_{inc}	=	incidental to design pressure ration (for selection guidance see /8/)

p_{corr} is calculated according to [3.7.3], [3.7.4] and/or [3.7.5].

For pipeline with long axial corrosion defects system effects need to be taken into account ([3.6]), and p_{corr} needs to be replaced with $p_{corr,\,syst}$ in the burst limit state given above.

If the acceptance criterion is not fulfilled, p_{corr} can be used to re-define the design pressure, p_d. In this case further corrosion shall also be accounted for, see [2.9]. The maximum allowable operating pressure is given as the design pressure including reduction over$p$ time due to further corrosion growth, minus the tolerance of the pressure control system (PCS). If p_d is changed, the MAOP has to be modified accordingly, see [1.13]/Figure 1-2.

3.7.3 Longitudinal corrosion defect, internal pressure loading only

3.7.3.1 Pressure resistance equation

The pressure resistance (p_{corr}) of a single metal loss defect subject to internal pressure loading is given by the following equation. The pressure resistance has not been validated for defects dimensions where the breadth (circumferential extent) of the defect exceeding the length of the defect.

$$p_{corr} = \gamma_m \cdot \frac{2tf_u}{(D-t)} \cdot \frac{\left(1-\gamma_d (d/t)^*\right)}{\left(1-\frac{\gamma_d (d/t)^*}{Q}\right)}$$

where:

$$Q = \sqrt{1 + 0.31\left(\frac{l}{\sqrt{Dt}}\right)^2}$$

$$(d/t)^* = (d/t)_{meas} + \varepsilon_d StD[d/t]$$

If γ_d $(d/t)^* \geq 1$ then $p_{corr} = 0$.

The acceptance criteria given in [3.7.2] shall be fulfilled.

3.7.3.2 Alternative applications

The form of the equation is made to determine the acceptable design pressure for a measured corrosion defect in a pipeline. In order to determine the acceptable measured defect size for a specified design pressure, the equation can be solved with respect to acceptable defect length as a function of measured defect depth by setting $0 < p_{li} - p_{le} = p_{corr}$ in the acceptance criterion in [3.7.2.2]. The maximum allowable defect length is then given as

$$l_{acc} = \sqrt{\frac{Dt}{0.31} \cdot \left[\left(\frac{\gamma_d (d/t)^*}{1 - \frac{p_0}{(p_{li} - p_{le})} \left(1 - \gamma_d (d/t)^*\right)} \right)^2 - 1 \right]}$$

where p_{li} and p_{le} are the local incidental and external pressure as defined in [3.7.2.2], and

$$p_0 = \gamma_m \frac{2\,t f_u}{(D - t)}$$

The equation is valid for $(1 - \gamma_d\,(d\,/\,t)^*) > 0$ and $p_o\,(1 - \gamma_d\,(d\,/\,t)^*) < p_{li} - p_{le} < p_0$. Maximum allowable defect curves are then obtained by varying the defect depth in the above equation, See Figure 2-5 and Figure 2-6.

3.7.3.3 Maximum acceptable defect depth

The requirement "γ_d $(d/t)^* \geq 1$ then $p_{corr} = 0$" considers the confidence in the sizing of the defect depth, and can also be expressed as:

$$(d/t)_{meas,\ acc} \leq 1/\gamma_d - \varepsilon_d StD[d/t]$$

The expression can also be determined from the above equation where short defect is assumed and hence Q = 1.

The maximum acceptable measured defect depths are dependent on the inspection method, sizing capabilities and safety or location class. Selected examples are given in Table 3-11.

Table 3-11 Maximum acceptable measured depth, selected examples

Safety class	*Inspection method*	*Accuracy*	*Conf. level*	*Max acceptable measured depth*
Medium	MFL	+/- 5%	80%	0.86 t [1)]
Medium	MFL	+/- 10%	80%	0.70 t
High	MFL	+/- 10%	80%	0.68 t
Medium	MFL	+/- 20%	80%	0.41 t
[1)] Limited to maximum 0.85 t, see [3.7.2.1].				

3.7.4 Longitudinal corrosion defect, internal pressure and superimposed longitudinal compressive stresses

The development of the method is outlined in /16/.

Compressive longitudinal stresses in a pipeline will reduce the burst capacity if the longitudinal stresses become significant. The pressure resistance of a single longitudinal corrosion defect subject to internal pressure and longitudinal compressive stresses can be estimated using the following procedure:

STEP 1 Determine the longitudinal stress, at the location of the corrosion defect, from external loads, as for instance axial, bending and temperature loads on the pipe. Calculate the nominal longitudinal elastic stresses in the pipe at the location of the corrosion defect, based on the nominal pipe wall thickness:

$$\sigma_A = \frac{F_X}{\pi(D-t)t}$$

$$\sigma_B = \frac{4M_Y}{\pi(D-t)^2 t}$$

The combined nominal longitudinal stress is: $\sigma_L = \sigma_A + \sigma_B$

STEP 2 If the combined longitudinal stress is compressive, then calculate the pressure resistance, including the correction for the influence of compressive longitudinal stress:

$$p_{corr,\ comp} = \gamma_m \cdot \frac{2 \cdot t \cdot f_u}{(D-t)} \cdot \frac{\left(1-\gamma_d (d/t)^*\right)}{\left(1-\frac{\gamma_d (d/t)^*}{Q}\right)} \cdot H_1$$

where:

$$H_1 = \frac{1+\frac{\sigma_L}{\xi f_u} \cdot \frac{1}{A_r}}{1-\frac{\gamma_m}{2\xi A_r} \cdot \frac{\left(1-\gamma_d (d/t)^*\right)}{\left(1-\frac{\gamma_d (d/t)^*}{Q}\right)}}$$

$$A_r = \left(1-\frac{d}{t}\theta\right)$$

$\sigma_L < 0$ and $p_{corr,comp}$ is limited by p_{corr} /16/.

The acceptance criteria given in [3.7.2] shall be fulfilled (for $p_{corr,comp}$).

3.7.5 Circumferential corrosion defects, internal pressure and superimposed longitudinal compressive stresses

The acceptance equation given below is not valid for full circumference corrosion defects with a longitudinal length exceeding 1.5t. The pressure resistance of a single ppcircumferential corrosion defect can be estimated using the following procedure:

STEP 1 Determine the longitudinal stress, at the location of the corrosion defect, from external loads, as for instance axial, bending and temperature loads on the pipe. Calculate the nominal longitudinal elastic stresses in the pipe, based on the nominal pipe wall thickness:

$$\sigma_A = \frac{F_x}{\pi(D-t)t}$$

$$\sigma_B = \frac{4M_Y}{\pi(D-t)^2 t}$$

The combined nominal longitudinal stress is: $\sigma_L = \sigma_A + \sigma_B$

STEP 2 If the combined longitudinal stress is compressive, then calculate the pressure resistance, including the correction for the influence of compressive longitudinal stress:

$$p_{corr,\ circ} = \min\left(\gamma_{mc}\frac{2\ tf_u}{(D-t)}\left(\frac{1+\frac{\sigma_L}{\xi f_u}\frac{1}{A_r}}{1-\frac{\gamma_{mc}}{2\xi}\frac{1}{A_r}}\right),\ \gamma_{mc}\frac{2\ tf_u}{(D-t)}\right)$$

where:

$$A_r = \left(1-\frac{d}{t}\theta\right)$$

The acceptance criteria given in [3.7.2] shall be fulfilled.

The longitudinal pipe wall stress in the remaining ligament is not to exceed ηf_y, in tension or in compression. The longitudinal pipe wall stress shall include the effect of all loads, including the pressure.

$$|\ \sigma_{L\text{-}nom}\ | \le \eta\ f_y(\ 1 - (d\ /\ t))$$

where: $\sigma_{L\text{-}nom}$ is the longitudinal stress in the nominal pipe wall.

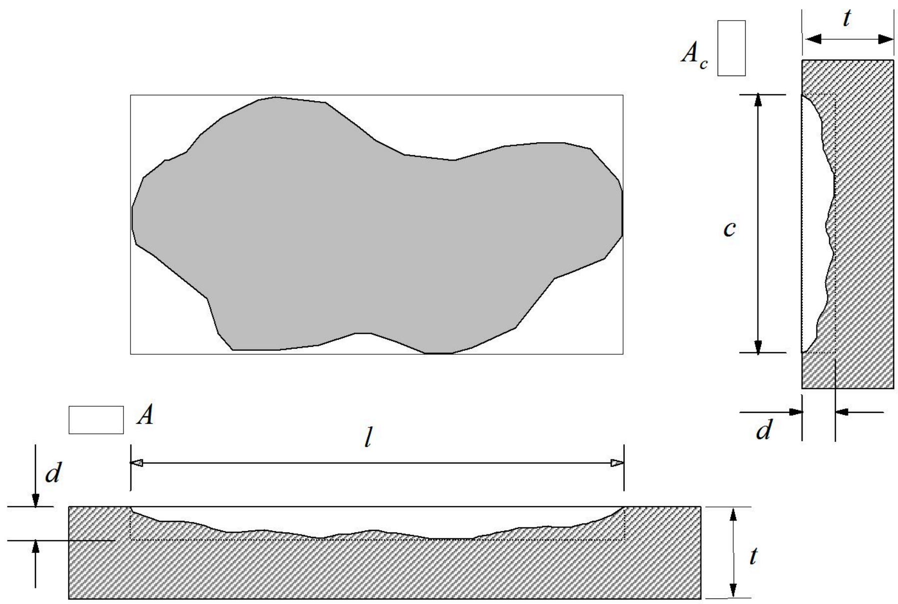


Figure 3-5 Single defect dimensions

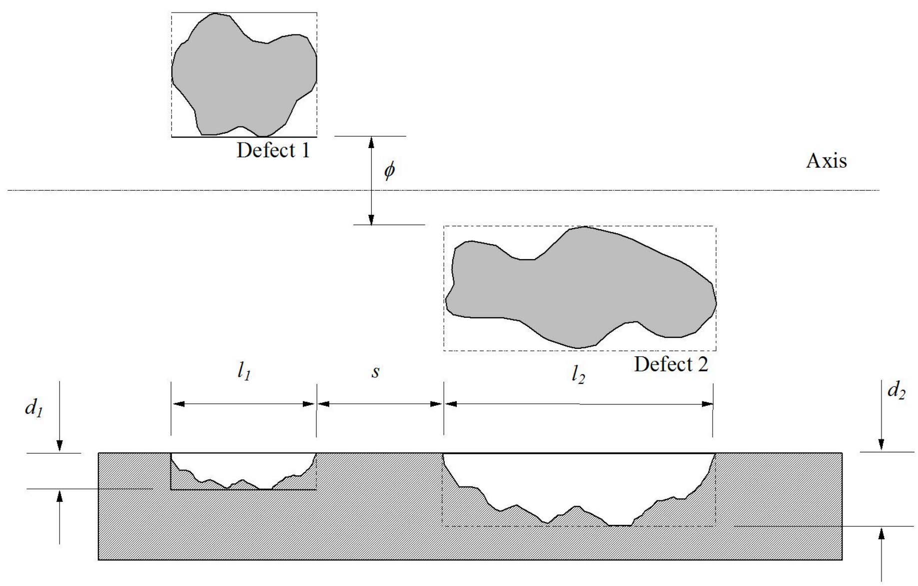


Figure 3-6 Interacting defect dimensions

3.8 Assessment of interacting defects

3.8.1 Requirements

The interaction rules are strictly valid for defects subject to only internal pressure loading. The rules may be used to determine if adjacent defects interact under other loading conditions, at the judgement of the user. However, using these interaction rules may be non-conservative for other loading conditions. The minimum information required comprises:

— The angular position of each defect around circumference of the pipe.
— The axial spacing between adjacent defects.
— Whether the defects are internal or external.
— The length of each individual defect.
— The depth of each individual defect.
— The width of each individual defect.

3.8.2 Pressure resistance estimate

The partial safety factors for interacting defects have not been derived from an explicit probabilistic calibration. The partial safety factors for a single defect subject to internal pressure loading have been used.

The pressure resistance of a colony of interacting defects can be estimated using the following procedure:

Guidance note:

Within the colony of interacting defects, all single defects, and all combinations of adjacent defects, are considered in order to determine the minimum predicted pressure resistance.

Combined defects are assessed with the single defect equation, using the total length (including spacing) and the effective depth (based on the total length and a rectangular approximation to the corroded area of each defect within the combined defect).

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 1 For regions where there is background metal loss (less than 10% of the wall thickness) the local pipe wall thickness and defect depths can be used (see Figure 3-7).

STEP 2 The corroded section of the pipeline should be divided into sections of a minimum length of

$$5.0\sqrt{Dt}$$

, with a minimum overlap of

$$2.5\sqrt{Dt}$$

Steps 3 to 12 should be repeated for each sectioned length to assess all possible interactions.

STEP 3 Construct a series of axial projection lines with a circumferential angular spacing of:

$$Z = 360\sqrt{\frac{t}{D}} \quad \text{degrees}$$

STEP 4 Consider each projection line in turn. If defects lie within ± Z, they should be projected onto the current projection line (see Figure 3-8).

STEP 5 Where defects overlap, they should be combined to define a form of composite defect. For internal or external defects, the composite defect is formed by using the depth of the deepest defect only where they overlap (see Figure 3-9). If the composite defect consists of an overlapping internal and external defect then the depth of the composite defect is the sum of the maximum depth of the internal and external defects (see guidance note above and Figure 3-10).

STEP 6 Calculate the pressure resistance ($p_1, p_2 \dots p_N$) of each defect, to the N^{th} defect, treating each defect, or composite defect, as a single defect:

$$p_i = \gamma_m \cdot \frac{2\, t f_u}{(D-t)} \cdot \frac{\left(1-\gamma_d \left(d_i/t\right)^*\right)}{\left(1-\frac{\gamma_d \left(d_i/t\right)^*}{Q_i}\right)}$$

i = 1…N

where:

$$Q_i = \sqrt{1+0.31\left(\frac{l_i}{\sqrt{Dt}}\right)^2}$$

$$(d_i/t)^* = (d_i/t)_{meas} + \varepsilon_d StD[d/T]$$

If $\gamma_d\,(d/t)^* \geq 1$ then $p_i = 0$.

Guidance note:

Steps 7 to 9 estimate the pressure resistance of all combinations of adjacent defects. The pressure resistance of the combined defect *nm* (i.e. defined by single defect *n* to single defect *m*, where $n = 1 \dots N$ and $m = n \dots N$) is denoted p_{nm}.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 7 Calculate the combined length of all combinations of adjacent defects (see Figure 3-11 and Figure 3-12). For defects *n* to *m* the total length is given by:

$$l_{nm} = l_m + \sum_{i=n}^{i=m-1}\left(l_i + s_i\right)$$

n,m = 1…N

STEP 8 Calculate the effective depth of the combined defect formed from all of the interacting defects from *n* to *m*, as follows (see Figure 3-11):

$$d_{nm} = \frac{\sum_{i=n}^{i=m} d_i l_i}{l_{nm}}$$

STEP 9 Calculate the pressure resistance of the combined defect from *n* to *m* (p_{nm}) (see Figure 3-12, using l_{nm} and d_{nm} in the single defect equation:

$$p_{nm} = \gamma_m \cdot \frac{2\, t f_u}{(D-t)} \cdot \frac{\left(1-\gamma_d \left(d_{nm}/t\right)^*\right)}{\left(1-\frac{\gamma_d \left(d_{nm}/t\right)^*}{Q_{nm}}\right)} \quad \text{n,m = 1…N}$$

where:

$$Q_{nm} = \sqrt{1 + 0.31\left(\frac{l_{nm}}{\sqrt{Dt}}\right)^2}$$

$$(d_{nm}/t)^* \ (d_{nm}/t)_{meas} + \varepsilon_d StD[d_{nm}/t]$$

If $\gamma_d \, (d/t)^* \geq 1$ then $p_{corr} = 0$.

Note that ε_d and γ_d are functions of StD[d_{nm}/t].

Fully correlated depth measurements:

$$StD\left[d_{nm}/t\right] = \frac{\sum_{i=n}^{i=m} l_i StD\left[d_i/t\right]}{l_{nm}}$$

Guidance note:

The formula for StD[$d_{nm/t}$] assumes fully correlated depth measurements. In the case that the measurements are not fully correlated the uncertainty is reduced. The estimate and the effect of the applied measurement uncertainty need to be assessed and documented if the reduced uncertainty is to be used. In cases where the conditions are not known it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 10 The pressure resistance for the current projection line is taken as the minimum of the pressure resistances of all of the individual defects (p_1 to p_N), and of all the combinations of individual defects (p_{nm}), on the current projection line.

$$p_{corr} = min(p_1, p_2, ... p_N, p_{nm})$$

The acceptance criteria given in [3.7.2] shall be fulfilled.

STEP 11 The pressure resistance for the section of corroded pipe is taken as the minimum of the pressure resistances for each of the projection lines around the circumference.

STEP 12 Repeat steps 3 to 11 for the next section of the corroded pipeline.

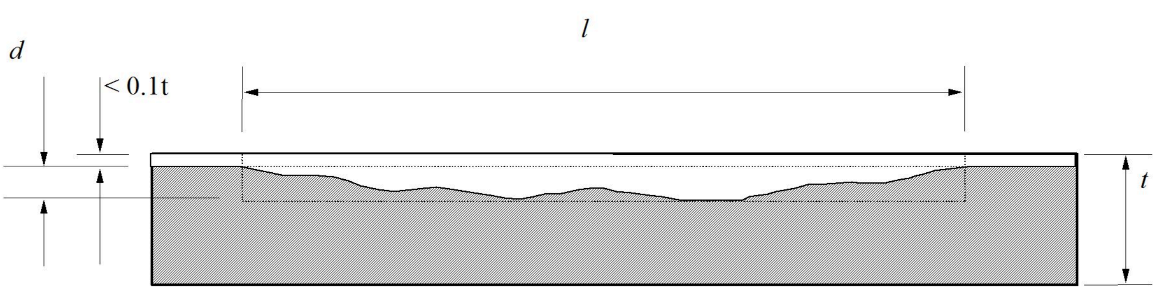


Figure 3-7 Corrosion depth adjustment for defects with background corrosion

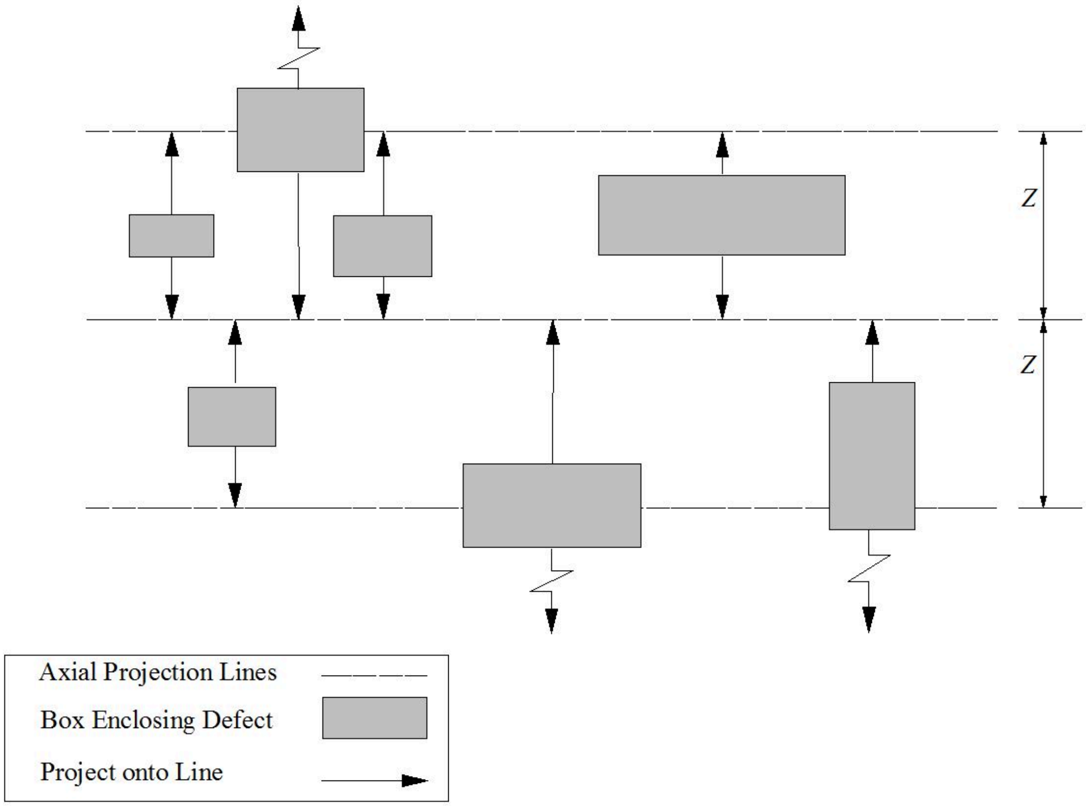


Figure 3-8 Projection of circumferentially interacting defects

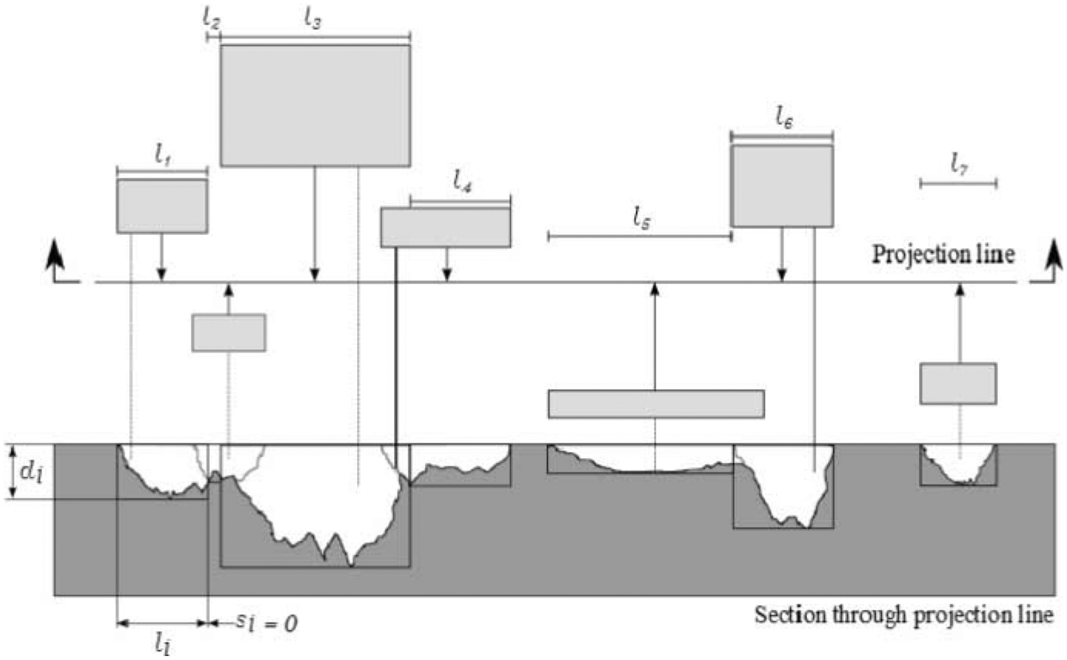


Figure 3-9 Projection of overlapping sites onto a single projection line and the formation of a composite defect

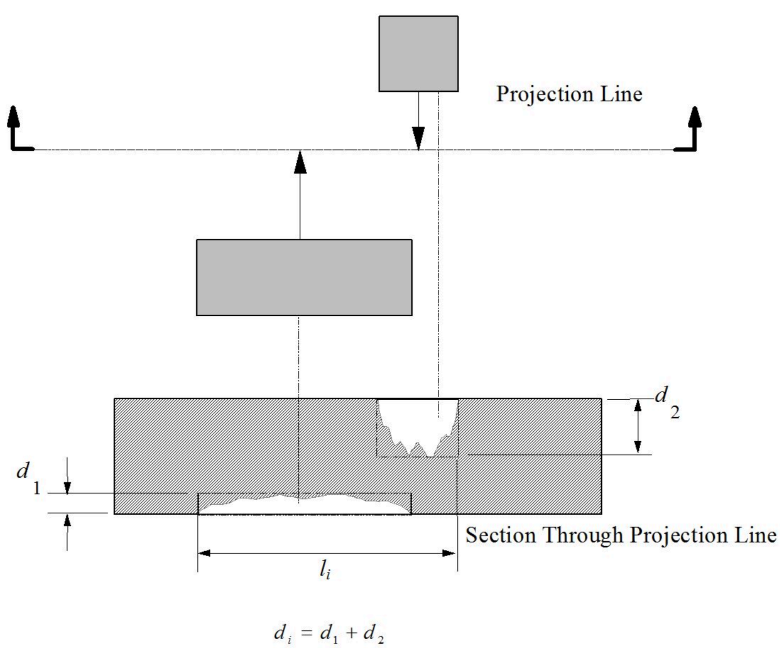
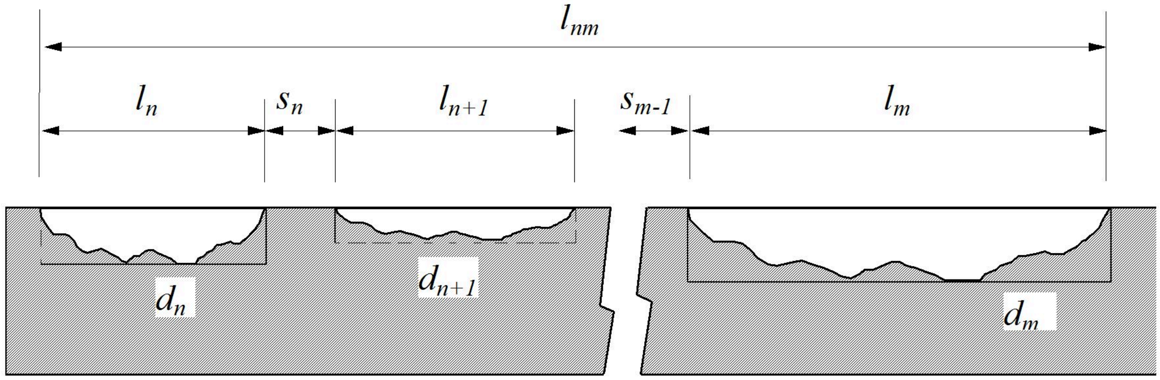


Figure 3-10 Projection of overlapping internal and external defects onto a single projection line and the formation of a composite defect



$$l_{nm} = l_m + \sum_{i=n}^{i=m-1} \left(l_i + s_i \right) \qquad d_{nm} = \frac{\sum_{i=n}^{i=m} d_i l_i}{l_{nm}}$$

Figure 3-11 Combining interacting defects

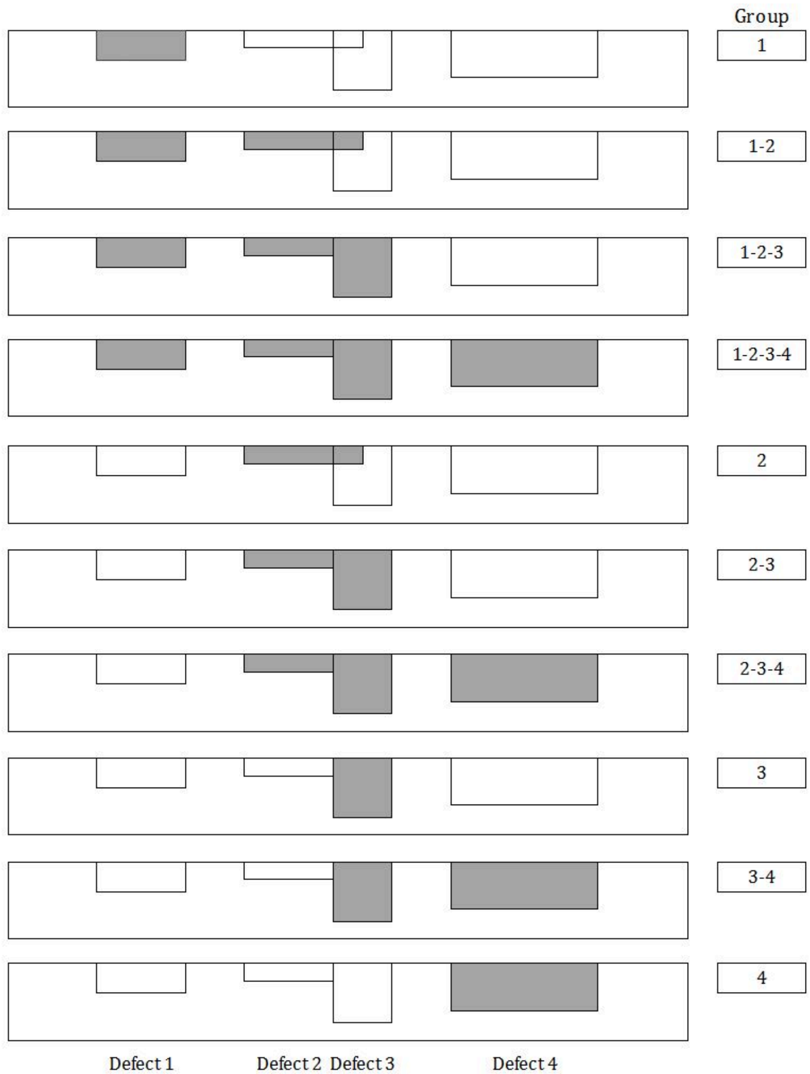


Figure 3-12 Example of the grouping of adjacent defects for interaction to find the grouping that gives the lowest estimated pressure resistance

3.9 Assessment of complex shaped defects

3.9.1 Requirements

This method shall only be applied to defects subjected to internal pressure loading only.

The minimum information required comprises:

1) A length and depth profile for the complex shape. The length is the axial length along the axis of the pipe. The defect depth, at a given axial length along the defect, should be the maximum depth around the circumference for that axial length (i.e. a river bottom profile of the defect).

2) The length of the profile shall include all material between the start and end of the complex shaped defect, but not more, and limited to a maximum length of

$$20 \cdot \sqrt{D \cdot t}$$

(i.e. the length should not include parts of the pipeline with no or insignificant corrosion).

Guidance on how to establish river bottom profiles from detailed UT inspection data can be found in [D.4].

3.9.2 Pressure resistance estimate

The partial safety factors for a complex shaped defect have not been derived from an explicit probabilistic calibration. The partial safety factors for a single defect subject to internal pressure loading have been used.

The pressure resistance of a complex shaped defect can be estimated using the following procedure:

Guidance note:

The principle underlying the complex shaped defect method is to determine whether the defect behaves as a single irregular patch, or whether local pits within the patch dominate the failure. Potential interaction between the pits has also to be assessed.

A progressive depth analyses is performed. The corrosion defect is divided into a number of increments based on depth.

At each depth increment, the corrosion defect is modelled by an idealised patch containing a number of idealised pits. The patch is the material loss shallower than the given increment depth. The pits are defined by the areas which are deeper than the increment depth, see Figure 3-13 and Figure 3-14. The pressure resistance of the pits within the 'patch' is estimated by considering an equivalent pipe of reduced wall thickness. The capacity (pressure resistance) of the equivalent pipe is equal to the capacity of the patch.

The idealised pits in the equivalent pipe are assessed using the interacting defect method (see [3.8]).

The estimated pressure resistance at a given depth increment, is the minimum of the pressure resistance of the patch, the idealised pits, and the pressure resistance of the total corroded area based on its total length and average depth.

The procedure is repeated for all depth increments in order to determine the minimum predicted pressure resistance. This is the pressure resistance of the complex shaped defect.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 1 Calculate the average depth (d_{ave}) of the complex shaped defect as follows:

$$d_{ave} = \frac{A}{l_{total}}$$

STEP 2 Calculate the pressure resistance of the total profile (p_{total}), using d_{ave} and l_{total} in the single defect equation:

$$p_{total} = \gamma_m \cdot \frac{2\,tf_u}{(D-t)} \cdot \frac{\left(1-\gamma_d\left(d_{ave}/t\right)^*\right)}{\left(1-\frac{\gamma_d\left(d_{ave}/t\right)^*}{Q_{total}}\right)}$$

where:

$$Q_{total} = \sqrt{1+0.31\left(\frac{l_{total}}{\sqrt{Dt}}\right)^2}$$

$$(d_{ave}/t)^* \; (d_{ave}/t)_{meas} + \varepsilon_d StD[d_{ave}/t]$$

If γ_d $(d_{ave}/t)^* \geq 1$ then $p_{total} = 0$.

Fully correlated depth measurements:

$$StD[d_{ave}/t] = StD[d/t]$$

Guidance note:

Note that ε_d and γ_d are functions of StD[d_{ave}/t].

The formula for StD[d_{ave}/t] assumes fully correlated depth measurements. In the case that the measurements are not fully correlated the uncertainty is reduced. The estimate and the effect of the applied measurement uncertainty need to be assessed and documented if the reduced uncertainty is to be used. In cases where the conditions are not known, it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 3 Divide the maximum defect depth into increments, and perform the below calculations for all depth increments (d_j) (see Figure 3-13). Each subdivision of the profile separates the profile into an idealised patch portion, shallower than the depth subdivision (i.e. the maximum depth of the patch is d_j), and into pits which are deeper than the subdivision (see Figure 3-14). The recommended number of increments is between 10 and 50.

STEP 4 Calculate the average depth of an idealised patch as follows (see Figure 3-14):

$$d_{patch} = \frac{A_{patch}}{l_{total}}$$

STEP 5 Calculate the pressure resistance of the idealised patch (p_{patch}) and the predicted capacity of the idealised patch ($p_{cap,patch}$), using l_{total} and d_{patch} in the single defect equation:

$$p_{patch} = \gamma_m \frac{2tf_u}{(D-t)} \frac{\left(1 - \gamma_d \left(d_{patch}/t\right)^*\right)}{\left(1 - \frac{\gamma_d \left(d_{patch}/t\right)^*}{Q_{total}}\right)}$$

Calculate also for use in step 7:

$$p_{cap,\ patch} = 1.09 \frac{2tf_u}{(D-t)} \frac{\left(1 - \left(d_{patch}/t\right)\right)}{\left(1 - \frac{\left(d_{patch}/t\right)}{Q_{total}}\right)}$$

where:

$$Q_{total} = \sqrt{1 + 0.31\left(\frac{l_{total}}{\sqrt{Dt}}\right)^2}$$

$$\left(d_{patch}/t\right)^* = \left(d_{patch}/t\right)_{meas} + \varepsilon_d StD\left[d_{patch}/t\right]$$

If γ_d $(d_{patch}/t)^* \geq 1$ then $p_{patch} = 0$.

Fully correlated depth measurements:

$$StD\left[d_{patch}/t\right] = Std[d/t]$$

Guidance note:

Note that ε_d and γ_d are functions of StD[d_{patch}/t].

The formula for StD[d_{patch}/t] assumes fully correlated depth measurements. In the case that the measurements are not fully correlated the uncertainty is reduced. The estimate and the effect of the applied measurement uncertainty need to be assessed and documented if the reduced uncertainty is to be used. In cases where the conditions are not known, it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 6 For each of the idealised pits, calculate the area loss in the nominal thickness cylinder, as shown in Figure 3-14, for the current depth interval, and estimate the average depth of each of the idealised pits from:

$$d_i = \frac{A_{i,pit}}{l_i} \qquad i = 1 \ldots N$$

STEP 7 Estimate the effective thickness of an equivalent pipe with the same pressure resistance as the patch, ($p_{cap,patch}$), as calculated in step 5 (see Figure 3-13).

$$t_e = \frac{p_{cap,patch} \cdot D}{\left(2\left(1.09 \cdot f_u\right) + p_{cap,\ patch}\right)}$$

STEP 8 The average depth of each pit is corrected for the effective thickness (t_e) using:

$$d_{ei} = d_i - \left(t - t_e\right)$$

STEP 9 Calculate the pressure resistance of all individual idealised pits (p_1, p_2, … p_N) as isolated defects, using the corrected average depth (d_{ei}), and the longitudinal length of the each idealised pit (l_i) in the single defect equation:

$$p_i = \gamma_m \frac{2t_e f_u}{\left(D - t_e\right)} \frac{\left(1 - \gamma_d\left(d_{ei}/t_e\right)^*\right)}{\left(1 - \frac{\gamma_d\left(d_{ei}/t_e\right)^*}{Q_i}\right)} \qquad i = 1 \ldots N$$

where:

$$Q_i = \sqrt{1 + 0.31\left(\frac{l_i}{\sqrt{Dt_e}}\right)^2}$$

$$\left(d_{ei,nm}/t_e\right)^* = \left(d_{ei,\ nm}/t_e\right)_{meas} + \varepsilon_d StD\left[d_{ei,\ nm}/t\right]$$

If γ_d $(d_{ei}/t_e)^* \geq 1$ then $p_i = 0$.

Guidance note:

Steps 10 to 12 estimate the pressure resistances of all combinations of adjacent defects. The pressure resistance of the combined defect *nm* (i.e. defined by single defect *n* to single defect *m*, where $n = 1 \ldots N$ and $m = n \ldots N$) is denoted p_{nm}.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 10 Calculate the combined length of all combinations of adjacent defects (see Figure 3-11 and Figure 3-12). For defects n to m the total length is given by:

$$l_{nm} = l_m + \sum_{i=n}^{i=m-1} \left(l_i + s_i\right) \qquad n,m = 1 \ldots N$$

STEP 11 Calculate the effective depth of the combined defect formed from all of individual idealised pits from n to m, as follows (see Figure 3-11):

$$d_{e,nm} = \frac{\sum_{i=n}^{i=m} d_{ei} l_i}{l_{nm}}$$

STEP 12 Calculate the pressure resistance of the combined defect from n to m (p_{nm}) (see Figure 3-12), using l_{nm}, t_e and $d_{e,nm}$ in the single defect equation:

$$p_{nm} = \gamma_m \frac{2t_e f_u}{(D-t_e)} \frac{\left(1-\gamma_d\left(d_{e,nm}/t_e\right)^*\right)}{\left(\frac{\left(1-\gamma_d\left(d_{e,nm}/t_e\right)^*\right)}{Q_{nm}}\right)} \qquad n,m = 1 \ldots N$$

where:

$$Q_{nm} = \sqrt{1 + 0.31\left(\frac{l_{nm}}{\sqrt{Dt_e}}\right)^2}$$

$$\left(d_{e,nm}/t_e\right)^* = \left(d_{e,nm}/t\right)_{meas} + \varepsilon_d StD\left[d_{e,nm}/t\right]$$

If $\gamma_d\ (d_{e,nm}/t_e)^* \geq 1$ then $p_{nm} = 0$.

Note that ε_d and γ_d are functions of StD[$d_{e,nm}/t$].

Fully correlated depth measurements:

$$StD\left[d_{e,nm}/t\right] = \frac{\sum_{i=n}^{i=m} l_i StD\left[d_{ei}/t\right]}{l_{nm}}$$

Guidance note:

The formula for StD[$d_{e,nm}/t$] assumes fully correlated depth measurements. In the case that the measurements are not fully correlated the uncertainty is reduced. The estimate and the effect of the applied measurement uncertainty need to be assessed and documented if the reduced uncertainty is to be used. In cases where the conditions are not known it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 13 The pressure resistance for the current depth increment is taken as the minimum of all the pressure resistances from above:

$$p_{corr_j} = \min\left(p_1, p_2, \ldots p_N, p_{nm}, p_{patch}, p_{total}\right)$$

STEP 14 Repeat the steps 4 to 13 for the next interval of depth increment (d_j) until the maximum depth of corrosion profile has been reached.

STEP 15 Calculate the pressure resistance according to the single defect equation in [3.7.3] using the maximum defect depth and the total length of the defect.

STEP 16 The pressure resistance of the complex shaped defect (p_{corr}) should be taken as the minimum of that from all of the depth intervals, but not less than the pressure resistance for a single defect calculated in step 15.

The acceptance criteria given in [3.7.2] shall be fulfilled.

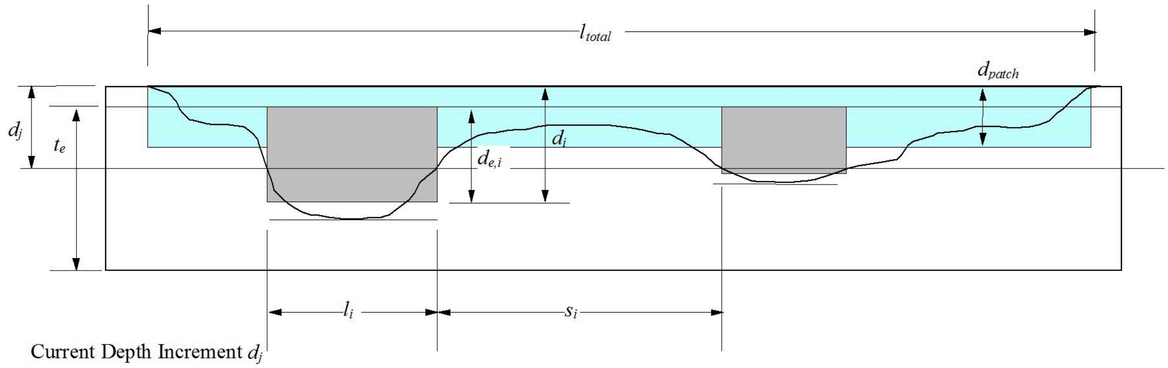


Figure 3-13 Subdivision of complex shape into idealised patch and pits

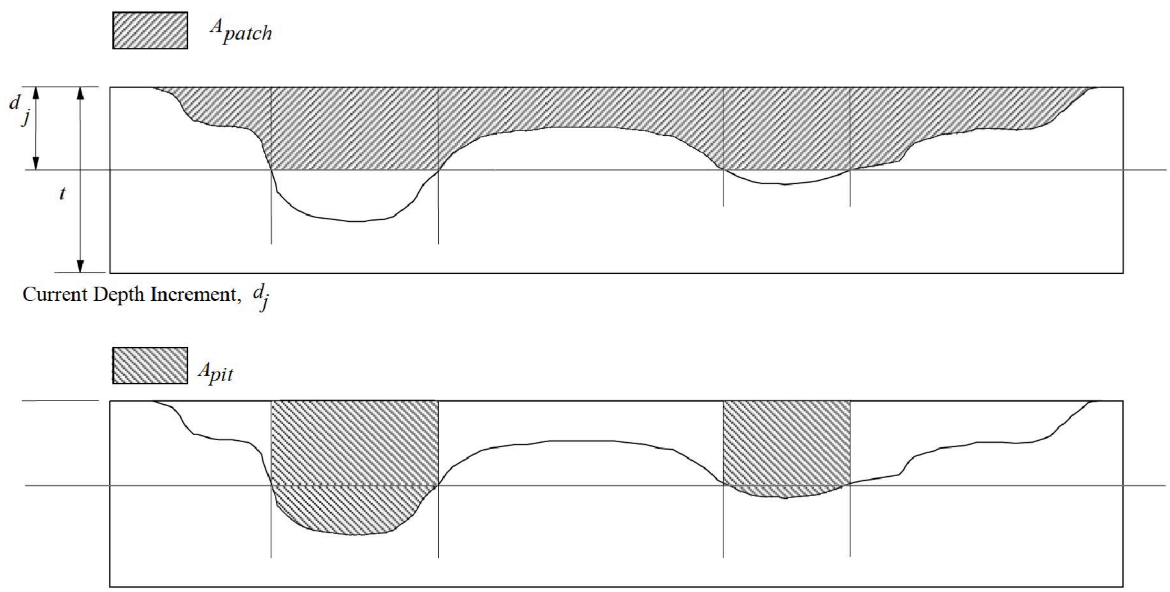


Figure 3-14 Definition of A_{patch} and A_{pit} for subdivision of complex shape into idealised patch and pits

SECTION 4 PART B - ALLOWABLE STRESS APPROACH

4.1 Introduction

The approach given in part B is based on the ASD (allowable stress design) format. The failure pressure of the pipeline with the corrosion defect is calculated, and this failure pressure is multiplied by a single safety factor based on the original design factor.

When assessing corrosion defects, due consideration should be given to the measurement uncertainty of the defect dimensions and the pipeline geometry.

4.2 Total usage factor

The usage factor to be applied in determining the safe working pressure has two components:

F_1	=	0.9 (modelling factor)
F_2	=	operational usage factor which is introduced to ensure a safe margin between the operating pressure and the failure pressure of the corrosion defect (and is normally taken as equal to the design factor).

The total usage factor (F) to be applied to determine the safe working pressure should be calculated from:

$$F = F_1 F_2$$

4.3 Assessment of a single defect

4.3.1 Requirements

Isolated metal loss defects shall be individually assessed as single defects, see Figure 3-5.

Adjacent defects can interact to produce a failure pressure that is lower than the individual failure pressures of the isolated defects treated as single defects. For the case where interaction occurs, the single defect equation is no longer valid and the procedure given in [4.4] shall be applied. Figure 3-6 shows the key dimensions for defect interaction.

A defect can be treated as an isolated defect, and interaction with other defects need not be considered, if either of the following conditions is satisfied:

1) The circumferential angular spacing between adjacent defects, φ:

$$\varphi > 360\sqrt{\frac{t}{D}} \text{ (degrees)}$$

2) The axial spacing between adjacent defects, s:

$$s > 2.0\sqrt{Dt}$$

4.3.2 Safe working pressure estimate - internal pressure only

The safe working pressure of a single defect subject to internal pressure loading only is given by the following equation:

STEP 1 Calculate the failure pressure of the corroded pipe (P_f):

$$P_f = \frac{2tf_u}{(D-t)} \frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)}$$

where:

$$Q = \sqrt{1+0.31\left(\frac{l}{\sqrt{Dt}}\right)^2}$$

STEP 2 Calculate the safe working pressure of the corroded pipe (P_{sw}):

$$P_{sw} = FP_f$$

Measured defects depths exceeding 85% of the wall thickness is not accepted.

Due consideration should be given to the measurement uncertainty of the defect dimensions and the pipeline geometry, which is not accounted for in the equations.

If the wall thickness is close to the required minimum remaining wall thickness, special care should be given. E.g. for a 10 mm wall thickness pipeline the minimum requirement is only 1.5 mm. Special attention should be given to these defects, both in term of reliability of the inspection methods and result and potential further growth.

4.3.3 Safe working pressure estimate - Internal pressure and combined compressive loading

The validation of the method for assessing corrosion defects subject to internal pressure and longitudinal compressive stresses is not as comprehensive as the validation of the method for assessing corrosion defects under internal pressure loading only.

Method for assessing a single defect subject to tensile longitudinal and/or bending stresses is given in e.g. /6/ and /11/.

The safe working pressure of a single corrosion defect subject to internal pressure and longitudinal compressive stresses can be estimated using the following procedure:

STEP 1 Determine the longitudinal stress, at the location of the corrosion defect, from external loads, as for instance axial, bending and temperature loads on the pipe. Calculate the nominal longitudinal elastic stresses in the pipe at the location of the corrosion defect, based on the nominal pipe wall thickness:

$$\sigma_A = \frac{F_X}{\pi(D-t)t}$$

$$\sigma_B = \frac{4M_Y}{\pi(D-t)^2 t}$$

The combined nominal longitudinal stresses is:

$$\sigma_L = \sigma_A + \sigma_B$$

STEP 2 Determine whether or not it is necessary to consider the effect of the external compressive longitudinal loads on the failure pressure of the single defect (see Figure 4-1).

It is not necessary to include the external loads if the loads are within the following limit:

$$\sigma_L > \sigma_1$$

where:

$$\sigma_1 = -0.5 f_u \frac{\left(1 - \frac{d}{t}\right)}{\left(1 - \frac{d}{tQ}\right)}$$

If the above condition is satisfied then step 4 can be neglected.

STEP 3 Calculate the failure pressure of the single corrosion defect under internal pressure only, using the following equation:

$$P_{press} = \frac{2 t f_u}{(D - t)} \frac{\left(1 - \frac{d}{t}\right)}{\left(1 - \frac{d}{tQ}\right)}$$

where:

$$Q = \sqrt{1 + 0.31\left(\frac{l}{\sqrt{Dt}}\right)^2}$$

STEP 4 Calculate the failure pressure for a longitudinal break, including the correction for the influence of compressive longitudinal stress (Figure 4-2):

$$P_{comp} = \frac{2 t f_u}{(D - t)} \frac{\left(1 - \frac{d}{t}\right)}{\left(1 - \frac{d}{tQ}\right)} H_1$$

where:

$$H_1 = \frac{1 + \frac{\sigma_L}{f_u}\frac{1}{A_r}}{1 - \frac{1}{2A_r}\frac{\left(1 - \frac{d}{t}\right)}{\left(1 - \frac{d}{tQ}\right)}}$$

$$A_r = \left(1 - \frac{d}{t}\theta\right)$$

STEP 5 Determine the failure pressure of a single corrosion defect subjected to internal pressure loading combined with compressive longitudinal stresses:

$$P_f = \min\left(P_{press}, P_{comp}\right)$$

STEP 6 Calculate the safe working pressure of the corroded pipe (P_{sw}):

$$P_{sw} = FP_f$$

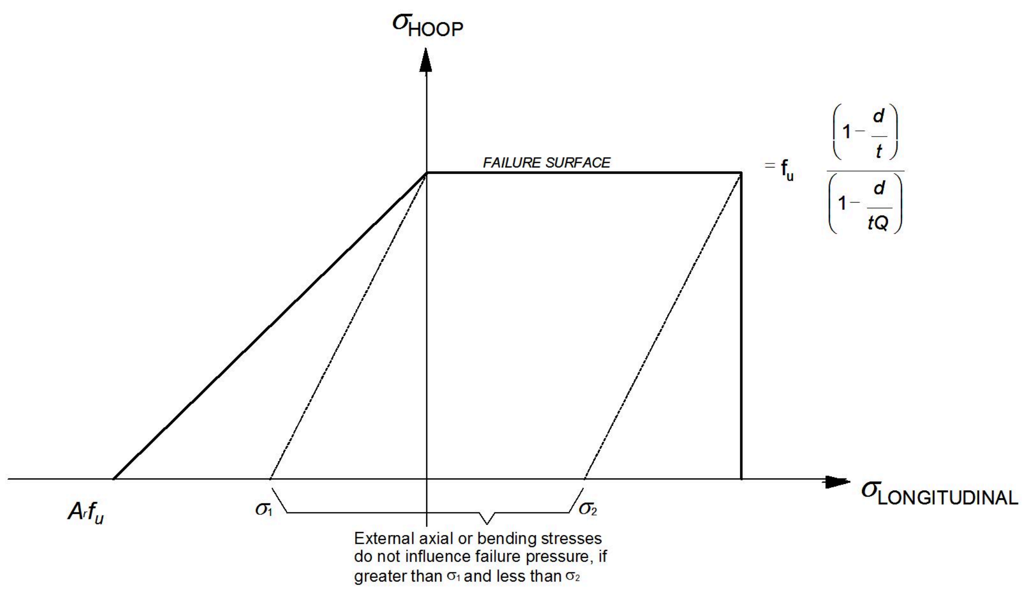


Figure 4-1 Range of superimposed longitudinal and/or bending loads that will not influence the failure pressure

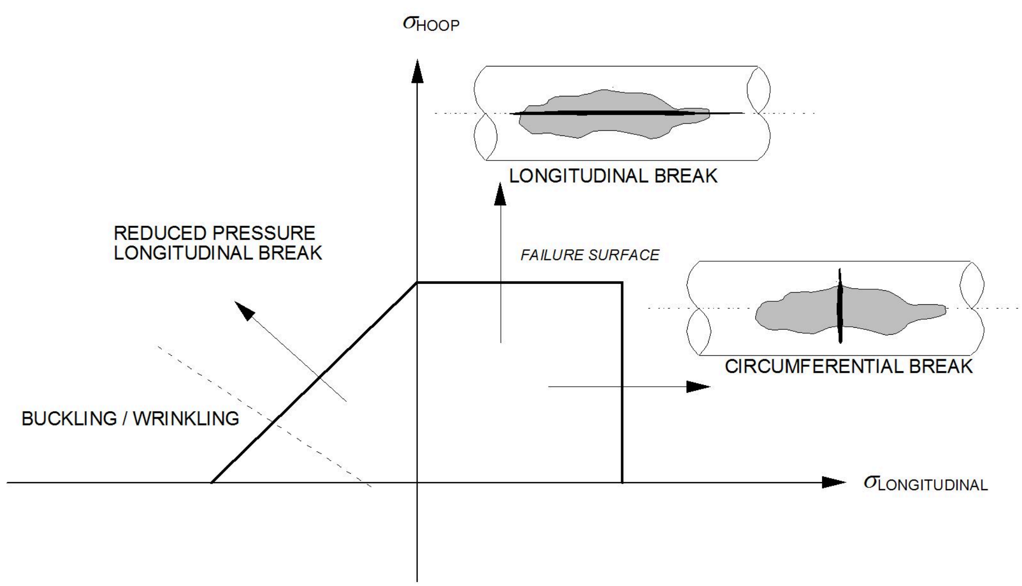


Figure 4-2 Influence of applied loads on the failure mode of a corrosion defect

4.4 Assessment of interacting defects

4.4.1 Requirements

The interaction rules are strictly valid for defects subject to only internal pressure loading. The rules may be used to determine if adjacent defects interact under other loading conditions, at the judgement of the user. However, using these interaction rules may be non-conservative for other loading conditions. The methods given in [4.3] for assessing corrosion defects under combined loads are only valid for single defects.

The minimum information required comprises:

— the angular position of each defect around circumference of the pipe
— the axial spacing between adjacent defects
— whether the defects are internal or external
— the length of each individual defect
— the depth of each individual defect
— the width of each individual defect.

4.4.2 Safe working pressure estimate

The safe working pressure can be estimated from the following procedure:

Guidance note:

Within the colony of interacting defects, all single defects, and all combinations of adjacent defects, are considered in order to determine the minimum safe working pressure.

Combined defects are assessed with the single defect equation, using the total length (including spacing) and the effective depth (calculated the total length and a rectangular approximation to the corroded area of each defect within the combined defect).

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 1 For regions where there is background metal loss (less than 10% of the wall thickness) the local pipe wall thickness and defect depths can be used (see Figure 3-7).

STEP 2 The corroded section of the pipeline should be divided into sections of a minimum length of $5.0\sqrt{Dt}$ with a minimum overlap of $2.5\sqrt{Dt}$. *Steps 3 to 12* should be repeated for each sectioned length to assess all possible interactions.

STEP 3 Construct a series of axial projection lines with a circumferential angular spacing of:

$$Z = 360\sqrt{\frac{t}{D}} \text{ (degrees)}$$

STEP 4 Consider each projection line in turn. If defects lie within ± Z, they should be projected onto the current projection line (see Figure 3-8).

STEP 5 Where defects overlap, they should be combined to form a composite defect. This is formed by taking the combined length, and the depth of the deepest defect, see Figure 3-9). If the composite defect consists of an overlapping internal and external defect then the depth of the composite defect is the sum of the maximum depth of the internal and external defects (see Figure 3-10).

STEP 6 Calculate the failure pressures (P_1, P_2 … P_N) of each defect, to the Nth defect, treating each defect, or composite defect, as a single defect:

$$P_i = \frac{2tf_u}{(D-t)}\frac{\left(1-\frac{d_i}{t}\right)}{\left(1-\frac{d_i}{tQ_i}\right)} \quad \text{i = 1…N}$$

where:

$$Q_i = \sqrt{1 + 0.31\left(\frac{l_i}{\sqrt{Dt}}\right)^2}$$

Guidance note:

Steps 7 to 9 estimate the failure pressures of all combinations of adjacent defects. The failure pressure of the combined defect *nm* (i.e. defined by single defect *n* to single defect *m*, where $n = 1 \ldots N$ and $m = n \ldots N$) is denoted P_{nm}.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 7 Calculate the combined length of all combinations of adjacent defects (see Figure 3-11 and Figure 3-12). For defects n to m the total length is given by:

$$l_{nm} = l_m + \sum_{i=n}^{i=m-1} \left(l_i + s_i\right) \quad n,m = 1 \ldots N$$

STEP 8 Calculate the effective depth of the combined defect formed from all of the interacting defects from *n* to *m*, as follows (see Figure 3-11):

$$d_{nm} = \frac{\sum_{i=n}^{i=m} d_i l_i}{l_{nm}}$$

STEP 9 Calculate the failure pressure of the combined defect from n to m (P_{nm}) (see Figure 3-12), using l_{nm} and d_{nm} in the single defect equation:

$$P_{nm} = \frac{2tf_u}{(D-t)} \frac{\left(1 - \frac{d_{nm}}{t}\right)}{\left(1 - \frac{d_{nm}}{tQ_{nm}}\right)}$$

where:

$$Q_{nm} = \sqrt{1 + 0.31\left(\frac{l_{nm}}{\sqrt{Dt}}\right)^2}$$

STEP 10 The failure pressure for the current projection line, is taken as the minimum of the failure pressures of all of the individual defects (P_1 to P_N), and of all the combinations of individual defects (P_{nm}), on the current projection line.

$$P_f = MIN\left(P_1, P_2, \ldots P_N, P_{nm}\right)$$

STEP 11 Calculate the safe working pressure (P_{sw}) of the interacting defects on the current projection line:

$$P_{sw} = FP_f$$

STEP 12 The safe working pressure for the section of corroded pipe is taken as the minimum of the safe working pressures calculated for each of the projection lines around the circumference.

STEP 13 Repeat steps 3 to 12 for the next section of the corroded pipeline.

4.5 Assessment of a complex shaped defect

4.5.1 Requirements

This method shall only be applied to defects subjected to internal pressure loading only.

The minimum information required comprises:

1) A length and depth profile for the complex shape. The length is the axial length along the axis of the pipe. The depth, at a given axial length along the defect, should be the maximum depth around the circumference for that axial length (i.e. a river bottom profile of the defect).
2) The length of the profile shall include all material between the start and end of the complex shaped defect, but not more, and limited to a maximum length of $20 \cdot \sqrt{D \cdot t}$ (i.e. the length should not include parts of the pipeline with no or insignificant corrosion).

4.5.2 Safe working pressure estimate

The safe working pressure of a complex shaped defect can be estimated from the following procedure:

Guidance note:

The principle underlying the complex shaped defect method is to determine whether the defect behaves as a single irregular patch, or whether local pits within the patch dominate the failure. Potential interaction between pits is also to be assessed.

A progressive depth analyses is performed. The corrosion defect is divided into a number of increments based on depth.

At each depth increment the corrosion defect is modelled by an idealised patch containing a number of idealised pits. The patch is the material loss shallower than the given increment depth. The pits are defined by the areas which are deeper than the increment depth, see Figure 3-13 and Figure 3-14. The failure pressure of the pits within the patch is estimated by considering an equivalent pipe of reduced wall thickness. The failure pressure of the equivalent pipe is equal to the failure pressure of the patch.

The idealised pits in the equivalent pipe are assessed using the interacting defect method (see [4.4]).

The estimated failure pressure at a given depth increment, is the minimum of the failure pressure of the patch, the idealised pits, and the failure pressure of the total corroded area based on its total length and average depth.

The procedure is repeated for all depth increments in order to determine the minimum predicted failure pressure. This is the failure pressure of the complex shaped defect.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 1 Calculate the average depth (d_{ave}) of the complex shaped defect as follows:

$$d_{ave} = \frac{A}{l_{total}}$$

STEP 2 Calculate the failure pressure of the total profile (P_{total}), using d_{ave} and l_{total} in the single defect equation:

$$P_{total} = \frac{2tf_u}{(D-t)} \frac{\left(1 - \frac{d_{ave}}{t}\right)}{\left(1 - \frac{d_{ave}}{tQ_{total}}\right)}$$

where:

$$Q_{total} = \sqrt{1 + 0.31\left(\frac{l_{total}}{\sqrt{Dt}}\right)^2}$$

STEP 3 Divide the maximum defect depth into increments, and perform the below calculations for all depth increments (d_j) (see Figure 3-13). Each subdivision of the profile separates the profile into an idealised patch portion, shallower than the depth subdivision (i.e. the maximum depth of the patch is d_j), and into pits which are deeper than the subdivision (see Figure 3-14). The recommended number of increments is between 10 and 50.

STEP 4 Calculate the average depth of an idealised patch as follows (see Figure 3-14):

$$d_{patch} = \frac{A_{patch}}{l_{total}}$$

STEP 5 Calculate the failure pressure of the idealised patch (P_{patch}), using l_{total} and d_{patch} in the single defect equation:

$$P_{patch} = \frac{2t\left(1.09 f_u\right)}{(D-t)} \frac{\left(1 - \frac{d_{patch}}{t}\right)}{\left(1 - \frac{d_{patch}}{tQ_{total}}\right)}$$

where:

$$Q_{total} = \sqrt{1 + 0.31\left(\frac{l_{total}}{\sqrt{Dt}}\right)^2}$$

STEP 6 For each of the idealised 'pits', calculate the area loss in the nominal thickness cylinder, as shown in Figure 3-14, for the current depth interval, and estimate the average depth of each of the idealised pits from:

$$d_i = \frac{A_{i,pit}}{l_i} \quad \text{i = 1...N}$$

STEP 7 Estimate the effective thickness of an 'equivalent' pipe with the same failure pressure as the patch, (P_{patch}), as calculated in step 5 (see Figure 3-13):

$$t_e = \frac{P_{patch} \cdot D}{\left(2\left(1.09 \cdot f_u\right) + P_{patch}\right)}$$

STEP 8 The average depth of each pit is corrected for the effective thickness (t_e) using:

$$d_{ei} = d_i - \left(t - t_e\right)$$

STEP 9 Calculate the failure pressure of all individual idealised pits (P_1, P_2, ... P_N) as isolated defects, using the 'corrected' average depth (d_{ei}) and the longitudinal length of the each idealised pit (l_i) in the single defect equation:

$$P_i = \frac{2t_e f_u}{(D-t_e)} \frac{\left(1-\frac{d_{ei}}{t_e}\right)}{\left(1-\frac{d_{ei}}{t_e Q_i}\right)}$$

where:

$$Q_i = \sqrt{1+0.31\left(\frac{l_i}{\sqrt{Dt_e}}\right)^2}$$

Guidance note:

Steps 10 to 12 estimate the failure pressures of all combinations of adjacent defects. The failure pressure of the combined defect *nm* (i.e. defined by single defect n to single defect *m*, where $n = 1 \ldots N$ and $m = n \ldots N$) is denoted P_{nm}.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

STEP 10 Calculate the combined length of all combinations of adjacent defects (see Figure 3-11 and Figure 3-12). For defects *n* to *m* the total length is given by:

$$l_{nm} = l_m + \sum_{i=n}^{i=m-1} (l_i + s_i) \quad \text{n,m = 1...N}$$

STEP 11 Calculate the effective depth of the combined defect formed from all of individual idealised pits from *n* to *m*, as follows (see Figure 3-11):

$$d_{e,nm} = \frac{\sum_{i=n}^{i=m} d_{ei} l_i}{l_{nm}}$$

STEP 12 Calculate the failure pressure of the combined defect from n to m (P_{nm}) (see Figure 3-12), using l_{nm}, t_e and $d_{e,nm}$ in the single defect equation:

$$P_{nm} = \frac{2t_e f_u}{(D-t_e)} \frac{\left(1-\frac{d_{e,nm}}{t_e}\right)}{\left(1-\frac{d_{e,nm}}{t_e Q_{nm}}\right)}$$

where:

$$Q_{nm} = \sqrt{1+0.31\left(\frac{l_{nm}}{\sqrt{Dt_e}}\right)^2}$$

STEP 13 The failure pressure for the current depth increment is taken as the minimum of all the failure pressures from above:

$$P_{f_j} = \min\left(P_1, P_2, \ldots P_N, P_{nm} P_{patch}, P_{total}\right)$$

STEP 14 Repeat the steps 4 to 13 for the next interval of depth increment (d_j) until the maximum depth of corrosion profile has been reached.

STEP 15 Calculate the failure pressure according to the single defect equation in [4.3.2], step 1, using the maximum defect depth and the total length of the defect.

STEP 16 The failure pressure of the complex shaped defect (P_f) should be taken as the minimum of that from all of the depth intervals, but not less than the failure pressure for a single defect calculated in step 15.

STEP 17 Calculate the safe working pressure (P_{sw}) of the complex shaped defect:

$$P_{sw} = FP_f$$

SECTION 5 REFERENCES

5.1 References

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APPENDIX A EXAMPLES FOR PART A

A.1 Single defect assessment

Example 1

This example is for the assessment of an isolated corrosion defect under internal pressure loading (see [3.7.3]), using relative depth measurements.

The dimensions and material properties are summarised as follows:

Outside diameter	=	812.8 mm
Wall thickness	=	19.10 mm
SMTS	=	530.9 N/mm^2 (X65)
Defect length (max.)	=	200 mm
Defect depth (max.)	=	25% of wall thickness
The elevation of the defect/local pressure point	=	- 100 m
The elevation of reference point	=	+ 30 m
Seawater density	=	1025 kg/m^3
Containment density (typical gas)	=	200 kg/m^3
Material req. “U”	=	Not fulfilled
Design pressure (p_d)	=	150 bar
Design temperature	=	75°C
Incidental to design pressure ratio (γ_{inc})	=	1.1
Safety class	=	Medium

The defect dimensions have been taken from the results of an internal inspection using a magnetic flux intelligent pig. The inspection accuracy quoted by the inspection tool provider is that the defect depth will be reported with a ± 10% tolerance. This sizing accuracy is quoted with a confidence level of 80%.

StD[d/t] = 0.08 (from Table 3-3)

(alt. calc: StD[d/t] = acc_rel / Φ^{-1} (0.5 + conf/2) = 0.1 / Φ^{-1} (0.5 + 0.8/2) = 0.0780)

Taking the partial safety factors from Table 2-2, Table 3-2 and Table 3-7

α_U 0.96
γ_m 0.85
γ_d 1.28
ε_d 1.0

From Figure 2-3:

$f_{u,temp}$ = 15 N/mm2

Using the procedure for assessing single defects given in [3.7.3].

$$Q = \sqrt{1 + 0.31\left(\frac{l}{\sqrt{Dt}}\right)^2} = 1.3412$$

$$(d/t)^* = 0.25 + 1.0 \times 0.08 = 0.33$$

$$f_u\left(SMTS - f_{U,temp}\right) \cdot \alpha_U = \left(530.9\ N/mm^2\ - 15\ N/mm^2\right)\ \cdot 0.96 = 495.3\ N/mm^2$$

$$p_{corr} = 0.85\frac{2t \cdot f_U}{(D-t)}\frac{(1 - 1.28(d/t)^*)}{\left(1 - \frac{1.28(d/t)^*}{Q}\right)} = 17.08\ N/mm^2$$

The pressure containment shall fulfil the following criterion as described in [3.7.2.2].

$$p_{li} - p_{le} \le p_{corr} \qquad p_{le} = -\rho_{sw} \cdot g \cdot h_i$$

$$167.5bar - 10.05bar \le p_{corr} \qquad p_{li} = p_{inc} + \rho_{cont} \cdot g\left(h_{ref} - h_l\right)$$

$$157.5bar \le p_{corr}$$

The value of local incidental pressure minus local external pressure is 157.5 bar which is less than the pressure resistance (170.8 bar). The criterion is fulfilled, therefore the corrosion defect is acceptable at the current time.

Example 2

This example is for the assessment of an isolated corrosion defect under internal pressure loading (see [3.7.3]), using absolute depth measurements.

The dimensions and material properties are summarised as follows:

Outside diameter	=	812.8 mm
Wall thickness	=	19.10 mm
SMTS	=	530.9 N/mm^2 (X65)
Defect length (max.)	=	200 mm
Defect depth (max.)	=	4.8 mm (~ 25%)
The elevation of the defect/local pressure point	=	- 200 m
The elevation of reference point	=	+ 30 m
Seawater density	=	1025 kg/m^3
Containment density (typical gas)	=	200 kg/m^3
Material req. "U"	=	Not fulfilled
Design pressure (p_d)	=	150 bar
Design temperature	=	75°C
Incidental to design pressure ratio (γ_{inc})	=	1.1
Safety class	=	Medium

The defect dimensions have been taken from the results of an internal inspection using an ultrasonic intelligent pig. The inspection accuracy quoted by the inspection tool provider is that the defect depth will be reported with a ± 1.0 mm tolerance. This sizing accuracy is quoted with a confidence level of 80%.

Standard deviation is calculated as follows:

$$StD[d/t] = \sqrt{2}\ acc\_abs\ /\ (t \cdot \Phi^{-1}\ (0.5 + conf/2))$$

$$= \sqrt{2}\ 1.0\ /\ (19.1 * \Phi^{-1}\ (0.5 + 0.8/2)) = 0.058$$

(The more detailed calculation of the standard deviation would be 0.0422, see App.C or the 1999 version of the recommended practice)

Taking the partial safety factors from Table 2-2, Table 3-2 and Table 3-8.

α_U	0.96
γ_m	0.88

$$\gamma_d = 1 + 4.6StD\left[d/t\right] - 13.9StD[d/t]^2 = 1.22$$

$$\varepsilon_d = -1.33 + 37.5StD\left[d/t\right] - 104.2StD[d/t]^2 = 0.49$$

From Figure 2-3:

$f_{u,temp}$ = 15 N/mm^2 Tensile strength to be used to calculate the pressure resistance is:

$$f_u\left(SMTS - f_{u,\,temp}\right)\alpha_u = 495.3\ \ N/mm^2$$

Using the procedure for assessing single defects given in [3.7.3].

$$Q = \sqrt{1 + 0.31\left(\frac{l}{\sqrt{Dt}}\right)^2} = 1.3412$$

$$(d/t)^* = 0.25 + (0.49 \times 0.058) = 0.28$$

$$p_{corr} = 0.88\frac{2t.f_u}{(D-t)}\frac{(1 - 1.22(d/t)^*)}{\left(1 - \frac{1.22(d/t)^*}{Q}\right)} = 18.55\ \ N/mm^2$$

The pressure containment shall fulfil the following criterion as described in [3.7.2.2].

Criterion:	where:
$p_{li} - p_{le} \leq p_{corr}$	$p_{le} = -\rho_{sw} \cdot g \cdot h_l$
$169.51\ bar - 20.10\ bar \leq p_{corr}$	$p_{li} = p_{inc} + \rho_{cont} \cdot g\left(h_{ref} - h_l\right)$
$149.4\ bar \leq p_{corr}$	

The value of local incidental pressure minus local external pressure is 149.4 bar which is less than the pressure resistance (185.5 bar). The criterion is fulfilled, therefore the corrosion defect is acceptable at the current time.

Example 3

This example is for the assessment of an isolated longitudinal corrosion defect under internal pressure loading and superimposed longitudinal compressive stresses (see [3.7.4]).

The dimensions and material properties are summarised as follows:

Outside diameter	=	219.0 mm
Original wall thickness	=	14.5 mm
SMTS	=	455.1 N/mm^2 (X52)
Defect length (max.)	=	200.0 mm
Defect width (max.)	=	100.0 mm
Defect depth (max.)	=	62% of wall thickness
The elevation of the defect/local pressure point	=	- 100 m
The elevation of reference point	=	+ 30 m
Seawater density	=	1025 kg/m^3
Containment density (typical gas)	=	200 kg/m^3
Material req. "U"	=	Not fulfilled
Design pressure (p_d)	=	150 bar
Design temperature	=	100°C
Incidental to design pressure ratio (γ_{inc})	=	1.0
Safety class	=	Medium

The pipe is subject to a compressive longitudinal stress of magnitude 200 N/mm^2.

The defect dimensions have been taken from the results of an internal inspection using a magnetic flux intelligent pig. The inspection accuracy quoted by the inspection tool provider is that the defect depth will be reported with a ±10% tolerance. This sizing accuracy is quoted with a confidence level of 80%.

From Table 3-3 (assuming that the sizing accuracy follows a Normal distribution).

StD[d/t] = 0.08

Taking the partial safety factors from Table 2-2, Table 3-2, Table 3-7 and Table 3-10

α_U	0.96
γ_m	0.85
γ_d	1.28
ε_d	1.0
ξ	0.85

From Figure 2-3:

$f_{u,temp}$ = 30 N/mm2

$$f_u = \left(SMTS - f_{u,temp}\right) \cdot \alpha_u = 408.1 \ \mathrm{N}/mm^2$$

Using the procedure for assessing single defects given in [3.7.3].

$$Q = \sqrt{1 + 0.31\left(\frac{l}{\sqrt{Dt}}\right)^2} = 2.2147$$

$$(d/t)^* = 0.62 + 1.0 \times 0.08 = 0.70$$

$$p_{corr} = 0.85\frac{2t \cdot f_U}{(D-t)}\frac{(1-1.28(d/t)^*)}{\left(1-\frac{1.28(d/t)^*}{Q}\right)} = 8.59\ \mathrm{N}/mm^2$$

Using the procedure given in [3.7.4].

Step 1

Calculate the nominal longitudinal elastic stresses in the pipe, based on the nominal pipe wall thickness:

σ_L = –200 N/mm^2

Step 2

Calculate the pressure resistance, including the correction for the influence of compressive stresses:

$$\theta = \frac{c}{\pi D} = 0.1453$$

$$A_r = \left(1 - (d/t)_{meas}\theta\right) = 0.9098$$

$$H_1 = \frac{1 + \frac{\sigma_L}{0.85 f_U}\frac{1}{A_r}}{1 - \frac{0.85}{2 \times 0.85 A_r}\frac{(1-1.28(d/t)^*)}{\left(1-\frac{1.28(d/t)^*}{Q}\right)}} = 0.41$$

$$p_{corr,comp} = 0.85\frac{2t \cdot f_U}{(D-t)}\frac{(1-1.28(d/t)^*)}{\left(1-\frac{1.28(d/t)^*}{Q}\right)}H_1 = 3.48\ \mathrm{N}/mm^2$$

The pressure resistance under internal pressure corrected for the influence of longitudinal compressive stresses is 34.8 bar. The pressure containment shall fulfil the following criterion as described in [3.7.2.2] (using $p_{corr,comp}$)

Criterion:	where:
$p_{li} - p_{le} \le p_{corr}$	$p_{le} = -\rho_{sw} \cdot g \cdot h_l$
$152.5\ bar - 10.1\ bar \le p_{corr}$	$p_{li} = p_{inc} + \rho_{cont} \cdot g\left(h_{ref} - h_l\right)$
$142.5\ bar \ge p_{corr}$	

The value of local incidental pressure minus local external pressure is 142.5 bar which is higher than the $p_{corr,\ comp}$ (34.8 bar). The criterion is not fulfilled, therefore the corrosion defect is not acceptable at the current time. The pressure shall be downrated to a new design pressure and corresponding maximum allowable operating pressure until the corrosion defect is repaired. The new design pressure calculated based on $p_{corr,\ comp}$ is 42.3 bar for the current time.

$$\text{new }p_d = \frac{p_{corr,comp} + p_{le} - p_{con} \cdot g\left(h_{ref} - h_l\right)}{\gamma_{inc}} = \frac{34.8\,bar + 10.1\,bar - \left(200\,kg/m^3 \cdot 9.81\,m/s^2 \cdot (30\,m + 100\,m)\right)}{1.0} = 42.3\,bar$$

However, before deciding the final downrated pressures, the tolerance of the pipeline control system (see [1.13]) and any further corrosion development (see [2.9]) need to be taken into account.

A.2 Interacting defects

Example 4

This example is for a pair of rectangular patches 200 mm and 150 mm in length, respectively, and separated axially by 100 mm. The longer defect is 20% of the wall thickness deep and the shorter defect is 30% of the wall thickness deep.

The basic properties required by the assessment are:

Outside diameter	=	812.8 mm
Original wall thickness	=	20.1 mm
SMTS	=	530.9 N/mm^2 (X65)
Defect 1, length	=	200.0 mm
Defect 2, length	=	150.0 mm
Defect 1, width	=	20% of wall thickness
Defect 2, width	=	30% of wall thickness
The elevation of the defect/local pressure point	=	- 200 m
The elevation of reference point	=	+ 30 m
Seawater density	=	1025 kg/m^3
Containment density (typical oil)	=	800 kg/m^3
Material req. “U”	=	Not fulfilled
Design pressure (p_d)	=	150 bar
Design temperature	=	100°C
Incidental to design pressure ratio (γ_{inc})	=	1.1
Safety class	=	High

The defect dimensions have been taken from the results of an internal inspection using a magnetic flux intelligent pig. The inspection accuracy quoted by the inspection tool provider is that the defect depth will be reported with a ±10% tolerance. This sizing accuracy is quoted with a confidence level of 80%.

From Table 3-3, (assuming that the sizing accuracy follows a Normal distribution).

StD[d/t] = 0.08

Taking the partial safety factors from Table 2-2, Table 3-2 and Table 3-7

α_U	0.96
γ_m	0.80
γ_d	1.32
ε_d	1.0

Using the procedure for assessing interacting defects given in [3.8]:

The defects should be grouped into axial projections as described in steps 1 to 5 of [3.8.2].

Step 6 is to estimate the pressure resistance of both defects, when treated as isolated defects. The pressure resistances are 17.07 N/mm^2 and 16.79 N/mm^2 respectively.

Applying the rules for defect interactions in steps 7 to 9 gives:

Combined length (step 7)	=	450 mm
Effective depth (step 8)	=	0.19t

Assuming that the defect depth measurements are fully correlated:

$$StD\left[d_{nm}/t\right] = \frac{\sum_{i=n}^{i=m} l_i StD\left[d_i/t\right]}{l_{nm}} = 0.0622$$

Taking the partial safety factors from Table 3-2 and Table 3-7.

γ_m	0.80
γ_d	1.25
ε_d	0.60

Pressure resistance (step 9) = 16.05 N/mm^2

Step 10 is to select the minimum pressure resistance of the individual and combined defects. In this case, the pressure resistance of the combined defect is less than that of either of the single defects, which indicates that the defects interact.

The minimum pressure resistance is 16.05 N/mm^2 (160.5 bar). The pressure containment shall fulfil the following criterion as described in [3.7.2.2].

Criterion:	where:
$p_{li} - p_{le} \leq p_{corr}$	$p_{le} = -\rho_{sw} \cdot g \cdot h_l$
$183.0\ bar - 20.1\ bar \leq p_{corr}$	$p_{li} = p_{inc} + \rho_{cont} \cdot g\left(h_{ref} - h_l\right)$
$162.9\ bar \geq p_{corr}$	

The value of local incidental pressure minus local external pressure is 162.9 bar which is higher than the p_{nm} (160.5 bar). The criterion is not fulfilled, therefore the corrosion defect is not acceptable at the current time. The pressure shall be downrated to a new design pressure and corresponding maximum allowable operating pressure until the corrosion defect is repaired. The new design pressure calculated based on p_{nm} is 147.8 bar for the current time.

$$\text{new } p_d = \frac{p_{corr,comp} + p_{le} - p_{con} \cdot g \cdot \left(h_{ref} - h_l\right)}{\gamma_{inc}} = \frac{160.5\, bar + 20.1\ bar - \left(800\ kg/m^3 \cdot 9.81\, m/s^2 \cdot (30\, m + 100\, m)\right)}{1.1} = 147.8\, bar$$

However, before deciding the final downrated pressures, the tolerance of the pipeline control system (see [1.13]) and any further corrosion development (see Sec.2.9) need to be taken into account.

Example 5

This example is for a pair of overlapping rectangular patches 400 mm and 100 mm in length, respectively, and start at the same point in axial direction. The longer defect is 20% of the wall thickness deep and the shorter defect is 50% of the wall thickness deep.

The basic properties required by the assessment are:

Outside diameter	=	273 mm
Original wall thickness	=	12.7 mm
SMTS	=	530.9 N/mm^2 (X65)
The elevation of the defects/local pressure point	=	- 150 m
The elevation of reference point	=	+ 30 m
Seawater density	=	1025 kg/m^3
Containment density (typical oil)	=	800 kg/m^3
Material req. “U”	=	Not fulfilled
Design pressure (p_d)	=	200 bar
Design temperature	=	100°C
Incidental to design pressure ratio (γ_{inc})	=	1.1
Safety class	=	Medium

The defect dimensions have been taken from the results of an internal inspection using UT. The inspection accuracy quoted by the inspection tool provider is that the defect depth will be reported with a ±0.5 mm tolerance. This sizing accuracy is quoted with a confidence level of 90%.

From Table 3-3, (assuming that the sizing accuracy follows a Normal distribution):

StD[d/t] = 0.034

Taking the partial safety factors from Table 2-2, Table 3-2 and Table 3-8.

α_U	0.96
γ_m	0.88
γ_d	1.14
ε_d	0.0

From Figure 2-3:

$f_{U,temp}$= 30 N/mm^2

Tensile strength to be used to calculate the pressure resistance is:

$$f_U = \left(SMTS - f_{U,temp}\right) \cdot \alpha_u = \left(530.9\ \mathrm{N}/mm^2 - 30\ \mathrm{N}/mm^2\right) \cdot 0.96 = 480.9\ \mathrm{N}/mm^2$$

Using the procedure for assessing interacting defects given in [3.8]: The defects should be grouped into axial projections as described in steps 1 to 5 of [3.8.2].

Step 6 is to estimate the pressure resistance of both defects, when treated as isolated defects. The pressure resistance (p_{corr}) are 33.85 N/mm^2 and 30.31 N/mm^2 respectively.

By projecting the axial profile of the defects we get a composite defect, consisting of one defect with length 100 mm and depth 0.5t, and one defect with length 300 mm and depth 0.2t.

Applying the rules for defect interactions in steps 7 to 9 gives:

Combined length (step 7)	=	400 mm
Effective depth (step 8)	=	0.275t
Pressure resistance (step 9)	=	30.46 N/mm^2

Step 10 is to select the minimum pressure resistance of the individual and combined defects. In this case, the pressure resistance of the deepest single defect is lowest, which means that pressure resistance is governed by the deepest defect.

The pressure resistance is 30.31 N/mm^2 (303.1 bar). The pressure containment shall fulfil the following criterion as described in [3.7.2.2].

Criterion:	where:
$p_{li} - p_{le} \leq p_{corr}$	$p_{le} = -\rho_{sw} \cdot g \cdot h_l$
$234.1\ bar - 15.1\ bar \leq p_{corr}$	$p_{li} = p_{inc} + \rho_{cont} \cdot g\left(h_{ref} - h_l\right)$
$219.0\ bar \leq p_{corr}$	

The value of local incidental pressure minus local external pressure is 219.0 bar which is less than the pressure resistance (303.1 bar). The criterion is fulfilled, therefore the corrosion defect is acceptable at the current time.

A.3 Complex shaped defect

Example 6

The following worked example is for an actual corrosion defect for which the profile has been measured using a depth micrometer, (measured d and t)

The pipeline geometry and properties are summarised as follows:

Outside diameter	=	611.0 mm
Wall thickness	=	8.20 mm
SMTS	=	496.4 N/mm^2
The elevation of the defects/local pressure point	=	- 175 m

The elevation of reference point	=	+ 30 m
Seawater density	=	1025 kg/m^3
Containment density (typical oil)	=	800 kg/m^3
Material req. “U”	=	Fulfilled
Design pressure (p_d)	=	70 bar
Design temperature	=	50°C
Incidental to design pressure ratio (γ_{inc})	=	1.1
Safety class	=	Medium

The inspection accuracy quoted by the inspection tool provider is that the defect depth will be reported with a ± 0.1 mm tolerance. This sizing accuracy is quoted with a confidence level of 90%.

The defect profile is shown in Figure A-1 and the defect depths are tabulated in Table A-1. It is assumed that the depth measurements are fully correlated.

Table A-1 Tabulated profile for actual corrosion defect

Length [mm]	*Depth [mm]*
0	0
28.9	1
57.8	1.1
86.7	1.1
115.6	1.1
144.5	1.3
173.4	1.8
202.3	2.8
231.2	2.8
260.1	1.6
289	0

As single defect:

Using the procedure for assessing single defects given in [3.7], with a total length of 289 mm and maximum depth of 2.8 mm.

Calculation of standard deviation:

$StD[d/t] = \sqrt{2}\ acc\_abs / (t \cdot \Phi^{-1}(0.5 + conf/2))$

$= \sqrt{2}\ 1.0 / 8.2 * \Phi^{-1}(0.5 + 0.9/2) = 0.0105$

(The more detailed calculation of the standard deviation would be 0.0078, see App.C or the 1999 version of the recommended practice).

Taking the partial safety factor from Table 3-2.

$\gamma_m = 0.88$

Taking the partial safety factors from Table 3-8.

$$\gamma_d = 1 + 4.6\, StD[d/t] - 13.9\, StD[d/t]^2 = 1.046$$

$$\epsilon_d = 0.0$$

Pressure resistance = 8.92 N/mm^2

When the complex shaped defect is assessed as a single defect, using the total length and maximum depth, then the pressure resistance is 8.92 N/mm^2.

As single defect with average depth:

Using the procedure for assessing complex shaped defects given in [3.9]:

Single Defect Solution (steps 1 to 2)

Step 1 is to calculate the average depth of the defect from the projected total area loss of the defect. The total projected metal loss area is calculated to be 421.94 mm^2, resulting in an average depth of 1.46 mm for the length of 289 mm.

Step 2 is to estimate the pressure resistance of the defect from the average depth and the total length.

Assuming that the defect depth measurements are fully correlated:

$$\mathrm{StD}[d_{ave}/t] = \mathrm{StD}[d/t] = 0.0105$$

Safety factors as above.

Pressure resistance	=	10.45 N/mm^2

Progressive depth analysis (steps 3 to 15)

The profile was sectioned at 50 levels and the pressure resistance was estimated for each increment. Figure A-2 shows the variation of the pressure resistance estimate with depth. The minimum pressure resistance estimate was 10.10 N/mm^2 (100.1 bar). The section depth was 1.06 mm, which corresponds to the natural division between patch and pit, which can be seen in Figure A-1. The effect of the relatively distinct change in profile at this depth produces a sharp change in the estimated pressure resistance curve, as shown in Figure A-2.

Assuming that the defect depth measurements are fully correlated:

$\mathrm{StD}[d_{patch}/t] = \mathrm{StD}[d/t] = 0.0105$

Safety factors as above

Patch pressure resistance (step 5)	=	10.98 N/mm^2
Patch capacity pressure (step 5)	=	13.65 N/mm^2
Effective reduced thickness (step 7)	=	7.61 mm

Steps 6 to 12 are to estimate the pressure resistance of the idealised pits.

Step 9 is to estimate the pressure resistance of all individual idealised pits.

Step 12 is to estimate the pressure resistance of the combined defect from n to m.

Step 13 is to estimate the pressure resistance for the current horizontal step depth from the minimum of the patch and pit estimates. In this case the minimum pressure resistance is from the pit:

Minimum pressure resistance (step 13) = 10.1 N/mm^2.

In step 15 the defect is calculated as a single defect with the total length and the maximum depth. The allowable pressure is calculated as 8.92 N/mm^2 (89.2 bar).

Step 16 is to estimate the pressure resistance of the complete defect as the minimum of all the minimum estimates for each horizontal step, i.e. the minimum of all Step 13 results (see Figure A-2), but not less than the pressure from step 15.

Analysis of the defect as a complex profile, using the progressive depth method, gives a pressure resistance estimate of 10.1 N/mm^2.

The pressure resistance is 10.1 N/mm^2 (101 bar), if it is assumed that the depth measurements are fully correlated. The pressure containment shall fulfil the following criterion as described in [3.7.2.2].

Criterion:	where:
$p_{li} - p_{le} \leq p_{corr}$	$p_{le} = -\rho_{sw} \cdot g \cdot h_l$
$93.1\ bar - 17.6\ bar \leq p_{corr}$	$p_{li} = p_{inc} + \rho_{cont} \cdot g\left(h_{ref} - h_l\right)$
$75.5\ bar \leq p_{corr}$	

The value of local incidental pressure minus local external pressure is 75.5 bar which is less than the pressure resistance (101 bar). The criterion is fulfilled, therefore the corrosion defect is acceptable at the current time.

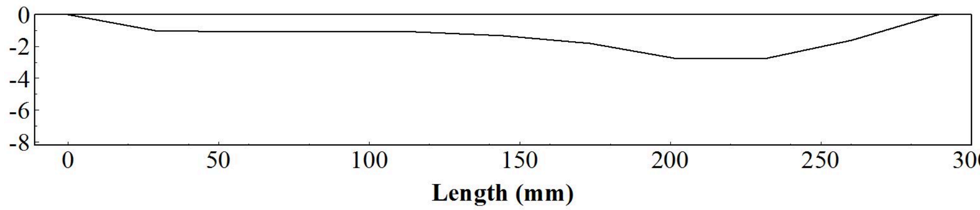

Figure A-1 Profile for actual corrosion defect - example assessment

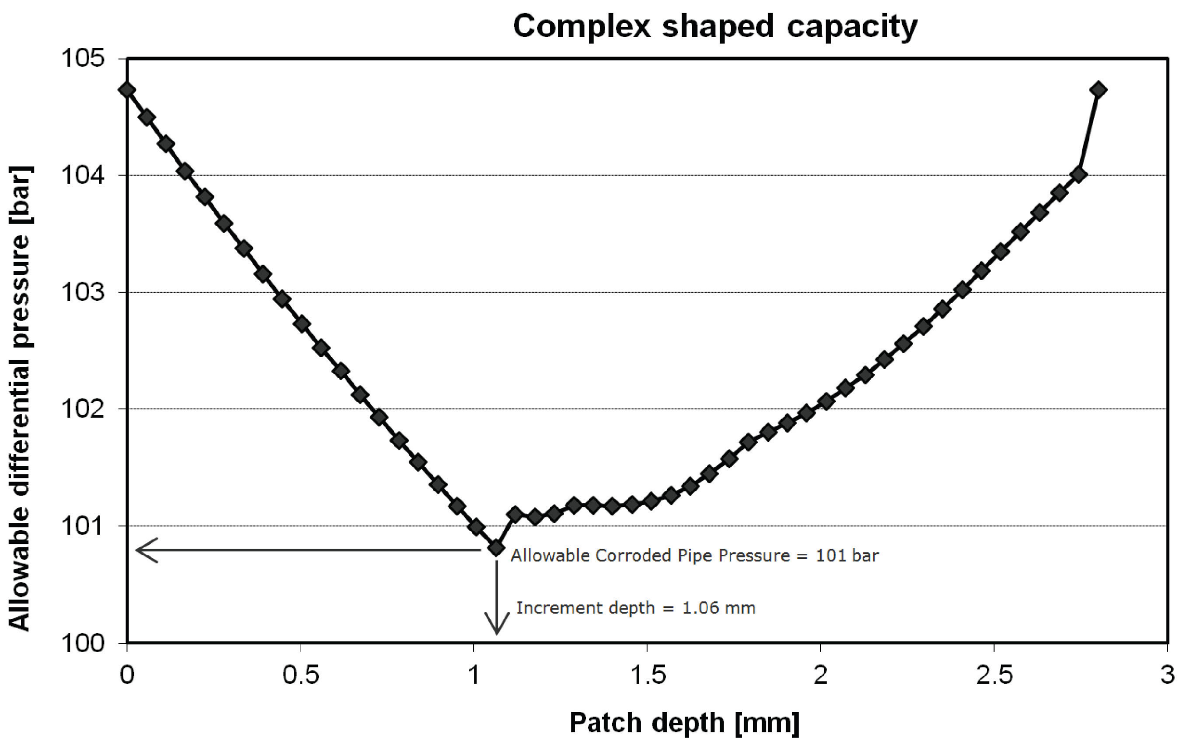

Figure A-2 Variations of the estimated pressure resistance for actual corrosion defect - example assessment

APPENDIX B EXAMPLES FOR PART B

B.1 Single defect assessment

Example 7

This example is for the assessment of an isolated corrosion defect under internal pressure loading only (see [4.3.2]).

The dimensions and material properties are summarised as follows:

Outside diameter	=	812.8 mm
Original wall thickness	=	19.10 mm
SMTS	=	530.9 N/mm^2 (X65)
Defect length (max.)	=	203.2 mm
Defect depth (max.)	=	13.4 mm

Using the procedure for assessing single defects given in [4.3.2].

Step 1 - Calculate the failure pressure using:

$$Q = \sqrt{1 + 0.31\left(\frac{l}{\sqrt{Dt}}\right)^2} = 1.350$$

f_u = SMTS

$$P_f = \frac{2tf_u}{(D-t)}\frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)} = 15.87\ \mathrm{N}/mm^2$$

Step 2 - Calculate a safe working pressure based on the factors of safety, and assuming a design factor of 0.72, gives:

The safe working pressure:

$$P_{sw} = (0.9)(0.72)P_f = 10.28\ \mathrm{N}/mm^2$$

(This compares with a burst pressure of 20.50 N/mm^2 from a full scale test, with measured ultimate tensile strength of 608 MPa. Using the ultimate tensile strength and the capacity equation including the 1.05 factor this will result in a capacity prediction of 19.1 N/mm^2, a deviation of about 7%).

Example 8

This example is for the assessment of an isolated corrosion defect under internal pressure and compressive longitudinal loading (see [4.3.3]).

The dimensions and material properties are summarised as follows:

Outside diameter	=	219.0 mm
Original wall thickness	=	14.5 mm
SMTS (= f_u)	=	455.1 N/mm^2 (X52)
Defect length (max.)	=	200.0 mm
Defect width (max.)	=	100.0 mm

Defect depth (max.)	=	62% of wall thickness

The pipe is subject to a compressive longitudinal stress of magnitude 200 N/mm^2.

Using the procedure for assessing single defects given in [4.3.3].

Step 1 - Calculate the nominal longitudinal elastic stresses in the pipe, based on the nominal pipe wall thickness:

$$\sigma_L = -200 \text{ N}/mm^2$$

Step 2- Assess whether it is necessary to consider the external loads:

$$\theta = \frac{c}{\pi D} = 0.1453$$

$$A_r = \left(1 - \frac{d}{t}\theta\right) = 0.9098$$

$$Q = \sqrt{1 + 0.31\left(\frac{l}{\sqrt{Dt}}\right)^2} = 2.2147$$

$$\sigma_1 = -0.5SMTS\frac{\left(1 - \frac{d}{t}\right)}{\left(1 - \frac{d}{tQ}\right)} = -119.92 \text{ N}/mm^2$$

Because $\sigma_L < \sigma_1$, step 4 cannot be neglected.

Step 3 - Calculate the failure pressure under the influence of internal pressure loading only:

$$Q = 2.2147$$

$$P_{press} = \frac{2tSMTS}{(D-t)}\frac{\left(1 - \frac{d}{t}\right)}{\left(1 - \frac{d}{tQ}\right)} = 34.01 \text{ N}/mm^2$$

Step 4 - Calculate the failure pressure for a longitudinal break, including the correction for the influence of compressive stresses:

$$H_1 = \frac{1 + \frac{\sigma_L}{SMTS}\frac{1}{A_r}}{1 - \frac{1}{2A_r}\frac{\left(1 - \frac{d}{t}\right)}{\left(1 - \frac{d}{tQ}\right)}} = 0.7277$$

$$P_{comp} = \frac{2tSMTS}{(D-t)}\frac{\left(1 - \frac{d}{t}\right)}{\left(1 - \frac{d}{tQ}\right)}H_1 = 24.75 \text{ N}/mm^2$$

Step 5 - Calculate the failure pressure:

$$P_f = \min\left(P_{press}, P_{comp}\right) = 24.75 \text{ N}/mm^2$$

Step 6 - Calculate a safe working pressure based on the factors of safety, and assuming a design factor of 0.72, gives:

$$P_{sw} = (0.9)(0.72)P_f = 16.04\ \mathrm{N}/mm^2$$

The safe working pressure is 16.04 N/mm^2.

B.2 Interacting defects

Example 9

This example is for a pair of rectangular patches 203.2 mm in length and separated axially by 81.3 mm. One defect is 14.2 mm deep and the other is 13.7 mm deep.

The basic properties required by the assessment are:

Outside diameter	=	812.8 mm
Original wall thickness	=	20.1 mm
SMTS	=	624.2 N/mm^2

Using the procedure for assessing interacting defects given in [4.4]:

The defects should be grouped into axial projections as described in steps 1 to 5 of [4.4.2].

Step 6 is to estimate the failure pressure of both defects, when treated as isolated defects. These pressures are 19.73 N/mm^2 and 20.59 N/mm^2 respectively.

Applying the rules for defect interactions in steps 7 to 9 for the combined defect gives:

Combined length (*Step 7*)	=	487.7 mm
Combined area	=	5669 mm^2
Effective depth (*Step 8*)	=	11.62 mm
Failure pressure (*Step 9*)	=	17.71 N/mm^2

Step 10 is to select the minimum of the individual and combined defects as the failure pressure. In this case, the failure pressure of the combined defect is less than the single defect solutions, indicating interaction. The failure pressure P_f of the defect is therefore 17.71 N/mm^2.

Step 11 is to calculate the safe working pressure from the estimated failure pressure, by applying the appropriate safety factors. For a design factor of 0.72, the safe working pressure is 11.48 N/mm^2.

B.2.1 Example 10

This example is for a pair of rectangular patches 203.2 mm in length and separated axially by 203.2 mm. The defects are 14.1 mm and 14.2 mm deep respectively.

The basic properties required by the assessment are:

Outside diameter	=	812.8 mm
Original wall thickness	=	20.1 mm
SMTS (=f_u)	=	624.2 N/mm^2

Using the procedure for assessing interacting defects given in [4.4]:

Steps 1 to 5 would be used to group the defects along a generator and estimate the projected profiles.

Step 6 is to estimate the failure pressure of both defects, when treated as isolated defects. The failure pressures are 19.90 N/mm^2 and 19.73 N/mm^2 respectively.

Applying the rules for defect interactions in steps 7 to 9 gives:

Combined length (step 7)	=	609.6 mm
Combined area	=	5751 mm^2
Effective depth (step 8)	=	9.43 mm
Failure pressure (step 9)	=	20.13 N/mm^2

Step 10 is to select the minimum of the individual and combined defects as the failure pressure. In this case, the failure pressure of the combined defect is slightly greater than that of either of the single defects, which suggests that there will be no interaction and that the pipe will fail at 19.73 N/mm^2.

Step 11 is to calculate the safe working pressure by applying the appropriate safety factors. For a design factor of 0.72, the safe working pressure is 12.79 N/mm^2.

B.3 Complex shaped defects

Example 11

This example is an analysis of the failure pressure of a complex shaped defect (see [4.5]). It is a large rectangular patch containing two adjacent deeper circular defects with semi-elliptical profiles.

The dimensions and material properties are summarised as follows, and a schematic of the defect is given in Figure B-1:

Outside diameter	=	762.0 mm
Original wall thickness	=	22.1 mm
SMTS (=f_u)	=	525.3 N/mm^2

The defect profile is shown in Figure B-1 and the exact depths are tabulated in Table B-1.

Table B-1 Tabulated profile complex shaped defect

Length [mm]	*Depth [mm]*
0	0
0	3.9
0.8	7.39
1.6	8.7
2.4	9.61
3.2	10.3
4	10.83
4.8	11.23
5.6	11.53
6.4	11.74
7.2	11.86
8	11.9
163	11.9

Length [mm]	*Depth* [mm]
169.2	12.42
175.4	13.41
181.5	14.28
187.7	15.04
193.9	15.67
200	16.19
206.2	16.59
212.3	16.87
218.4	17.04
224.5	17.1
230.6	17.04
236.7	16.87
242.8	16.59
249	16.19
255.1	15.67
261.3	15.04
267.5	14.28
273.6	13.41
279.8	12.42
286	11.3
292.2	12.42
298.4	13.41
304.5	14.28
310.7	15.04
316.9	15.67
323	16.19
329.2	16.59
335.3	16.87
341.4	17.04
347.5	17.1
353.6	17.04
359.7	16.87

Length [mm]	*Depth* [mm]
365.8	16.59
372	16.19
378.1	15.67
384.3	15.04
390.5	14.28
396.6	13.41
402.8	12.42
409	11.9
564	11.9
564.8	11.86
565.6	11.74
566.4	11.53
567.2	11.23
568	10.83
568.8	10.3
569.6	9.61
570.4	8.7
571.2	7.39
572	3.9
572	0

Using the procedure for assessing complex shaped defects given in [4.5]:
Single Defect Solution (steps 1 to 2)

Total length	=	572.0 mm
Maximum depth	=	17.1 mm

Step 1 is to calculate the average depth of the defect from the projected total area loss of the defect.

Total projected area loss	=	7584.6 mm^2
Average depth	=	13.26 mm

Step 2 is to estimate the failure pressure of the defect from the average depth and the total length.

Failure pressure	=	16.23 N/mm^2

Progressive Depth Analysis (steps 3 to 16)

The failure pressure was estimated for 50 increments in a progressive depth analysis. The variation in the failure pressure estimate, with respect to each step, is shown in Figure B-2.

Step 3 is to subdivide the defect into horizontal sections or depth increments and estimate the failure pressure for each section from steps 4 to 12.

Two examples of the analysis at various depths of horizontal section are given below:

Depth of increment no. 12	=	4.1 mm
Patch average area (step 4)	=	2347 mm^2
Patch length	=	572.0 mm
Patch average depth (step 4)	=	4.1 mm
Patch failure pressure (step 5)	=	27.47 N/mm^2

Steps 6 to 12 are to estimate the failure pressure of the idealised pits.

Number of pits = 1

Step 7 is to estimate the effective thickness of the pipe for the remaining pits.

Effective reduced thickness = 19.42 mm

Pit	*Average depth (mm) (step 6)*	*Average depth in reduced wall (mm) (step 8)*	*Length (mm)*	*Failure pressure (N/mm^2) (step 9)*
1	13.26	10.58	571.9	15.54

Pit interactions based on the reduced thickness pipe.

Step 13 is to estimate the failure pressure for the current horizontal step depth from the minimum of the patch and pit estimates. In this case the minimum pressure is from the pit:

Minimum pressure	=	15.54 N/mm^2
Depth of increment no. 38 (This is the section that gives the minimum pressure).	=	13.0 mm
Patch average area (step 4)	=	7019 mm^2
Patch length (step 4)	=	572.0 mm
Patch average depth (step 4)	=	12.59 mm
Patch failure pressure (step 5)	=	17.65 N/mm^2
Effective reduced thickness	=	12.59 mm

Number of pits = 2

Pit	*Average depth in nominal thickness pipe (mm)*	*Length (mm)*	*Separation to next pit*
1	15.73	103	19.6 mm
2	15.73	103	-

Pit interactions based on the reduced thickness pipe

Start pit	*End pit*	*Average depth in reduced wall (mm) (step 6-8)*	*Overall length (mm)*	*Failure pressure (N/mm^2) (step 9 or 10-12)*
1	1	6.22	103	15.56
1	2	5.69	226	13.40
2	2	6.22	103	15.56

Step 13 is to estimate the failure pressure for the current horizontal step depth from the minimum of the patch and pit estimates. In this case, the minimum pressure is from the pit interaction between pits 1 and 2:

Minimum pressure is due to interaction between pits 1 and 2	=	13.40 N/mm^2

In step 15 the defect is calculated as a single defect with the total length and the maximum depth. Using the procedure for assessing single defects given in [4.3.2].

Total length	=	572.0 mm
Maximum depth	=	17.1 mm
Failure pressure	=	10.03 N/mm^2

If this complex shaped defect is assessed as a single defect, based on the total length and maximum depth, then the predicted failure pressure is 10.03 N/mm^2.

Step 15 is to estimate the failure pressure of the complete defect, as the minimum of all the minimum estimates for each horizontal step, i.e. the minimum of all step 13 results but not less than the pressure from step 15, (see Figure B-4).

Analysis of the defect as a complex profile using the progressive depth method, without the application of a safety factor, gives a failure pressure estimate of 13.40 N/mm^2 from a section depth of 13.0 mm.

Step 17 is to estimate a safe working pressure from the estimated failure pressure. Applying the safety factors for a design factor of 0.72:

$$P_{sw} = (0.9)(0.72)P_f = 8.68\ \mathrm{N}/mm^2$$

The safe working pressure is 8.68 N/mm^2 (86.8 bar).

Example 12

This example is an analysis of the failure pressure of a smooth shaped complex shaped defect.

The pipeline geometry and properties are summarised as follows:

Outside diameter	=	611.0 mm
Wall thickness	=	8.20 mm
SMTS	=	571.0 N/mm^2

The defect profile is shown in Figure B-3 and the exact depths are tabulated in Table B-2.

Table B-2 Tabulated profile for actual corrosion defect

Length *[mm]*	*Depth* *[mm]*
0	0
28.9	1
57.8	1.1
86.7	1.1
115.6	1.1
144.5	1.3
173.4	1.8
202.3	2.8
231.2	2.8
260.1	1.6
289	0

Using the procedure for assessing complex shaped defects given in [4.5]:

Single Defect Solution (steps 1 to 2)

Total length	=	289.0 mm
Maximum depth	=	2.8 mm

Step 1 is to calculate the average depth of the defect from the projected total area loss of the defect.

Total projected area loss	=	421.94 mm^2
Average depth	=	1.46 mm

Step 2 is to estimate the failure pressure of the defect from the average depth and the total length.

Failure pressure	=	13.55 N/mm^2

Progressive depth analysis (steps 3 to 16)

The profile was sectioned at 50 levels and the failure pressure estimated for each increment. Figure B-4 shows the variation of the failure pressure estimate with depth. The minimum failure pressure estimate was 13.21 N/mm^2. The section depth was 1.09 mm; this corresponds to the natural division between patch and pit, which can be seen in Figure B-4. The effect of the relatively distinct change in profile at this depth produces a sharp change in the estimated failure pressure curve, as shown in Figure B-4.

The calculations at the section that produced the minimum failure pressures are presented as follows, as a typical example of the calculation which had to be performed at each section:

Step depth	=	1.06 mm
Patch average area (step 4)	=	280.4 mm^2
Patch length	=	289.0 mm
Patch average depth (step 4)	=	0.97 mm

Patch failure pressure (step 5) = 15.68 N/mm^2

Effective reduced thickness (step 7) = 7.60 mm

Steps 6 to 12 are to estimate the failure pressure of the idealised pits.

Number of pits = 1

Pit	*Average depth (mm)*	*Average depth on reduced wall (mm)*	*Length (mm)*	*Failure pressure (N/mm^2)*
1	1.700	1.100	222	13.22

Step 13 is to estimate the failure pressure for the current horizontal step depth from the minimum of the patch and pit estimates. In this case the minimum pressure is from the pit:

Minimum pressure = 13.22 N/mm^2

Step 15 is to estimate the failure pressure of the complete defect as the minimum of all the minimum estimates for each horizontal step, i.e. the minimum of all step 13 results (see Figure B-4).

Analysis of the defect as a complex profile using the progressive depth method, without the application of a safety factor, gives a failure pressure estimate of 13.21 N/mm^2.

In step 15 the defect is calculated as a single defect with the total length and the maximum depth

Using the procedure for assessing single defects given in [4.3].

Total length = 289.0 mm

Maximum depth = 2.8 mm

Failure pressure = 11.86 N/mm^2

If this complex shaped defect is assessed as a single defect, based on the total length and maximum depth, then the predicted failure pressure is 11.86 N/mm^2.

Step 16 is to estimate the pressure resistance of the complete defect as the minimum of all the minimum estimates for each horizontal step, i.e. the minimum of all step 13 results, but not less than the pressure from step 15.

Step 17 is to calculate the safe working pressure from the estimated failure pressure. Applying the safety factors for a design factor of 0.72:

$$P_{sw} = (0.9)(0.72)P_f = 8.56 \ \mathrm{N}/mm^2$$

The safe working pressure is 8.56 N/mm^2 (85.6 bar).

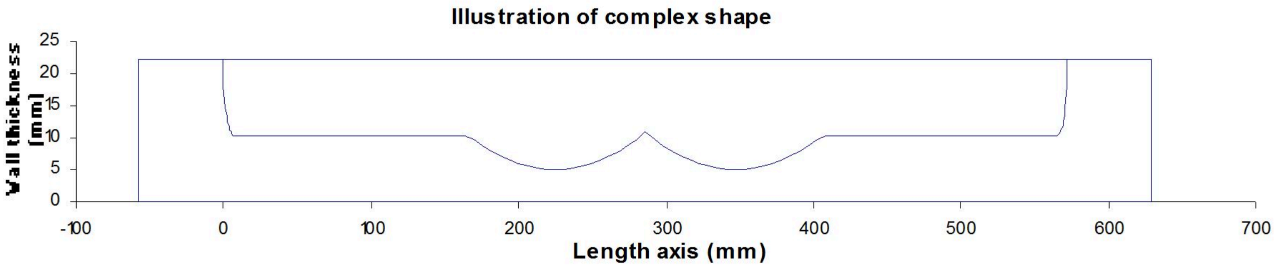

Figure B-1 Profile for complex shaped defect - Example assessment

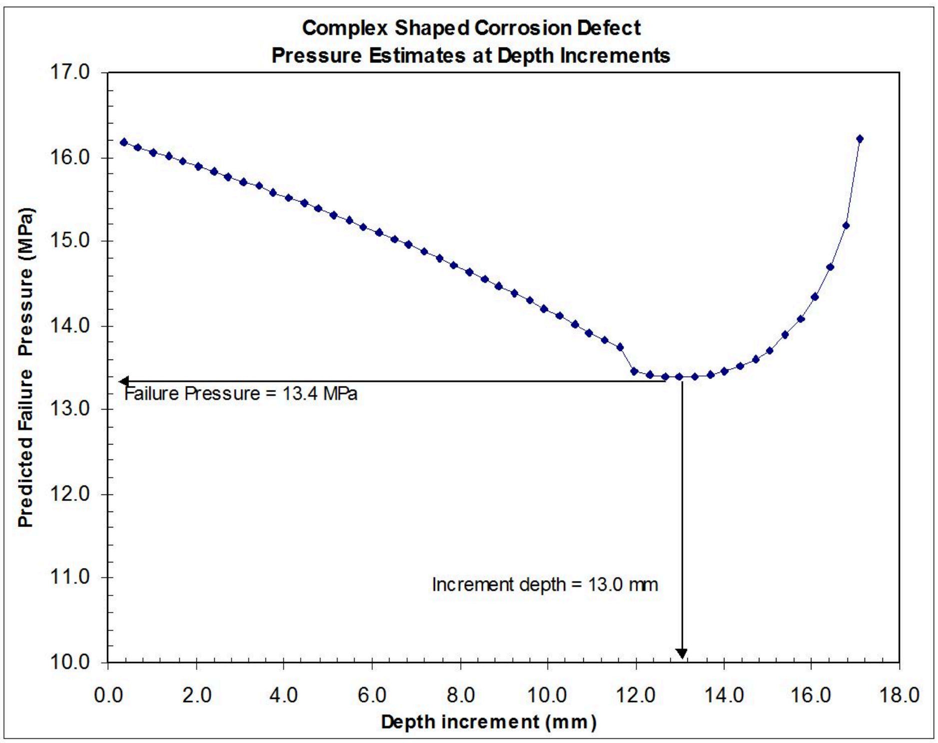

Figure B-2 Variations of the estimated failure pressure for complex shaped defect - Example assessment

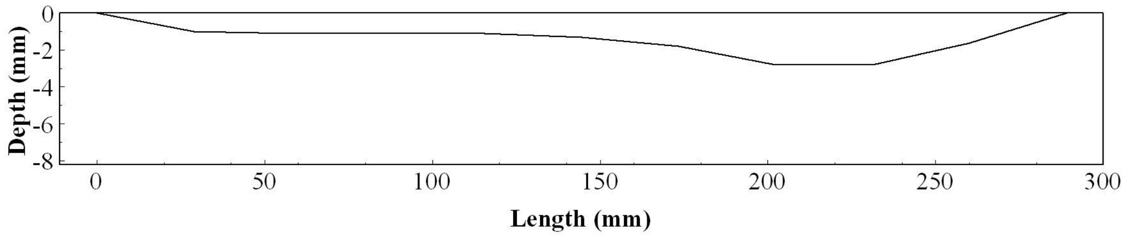

Figure B-3 Profile for actual corrosion defect - Example assessment

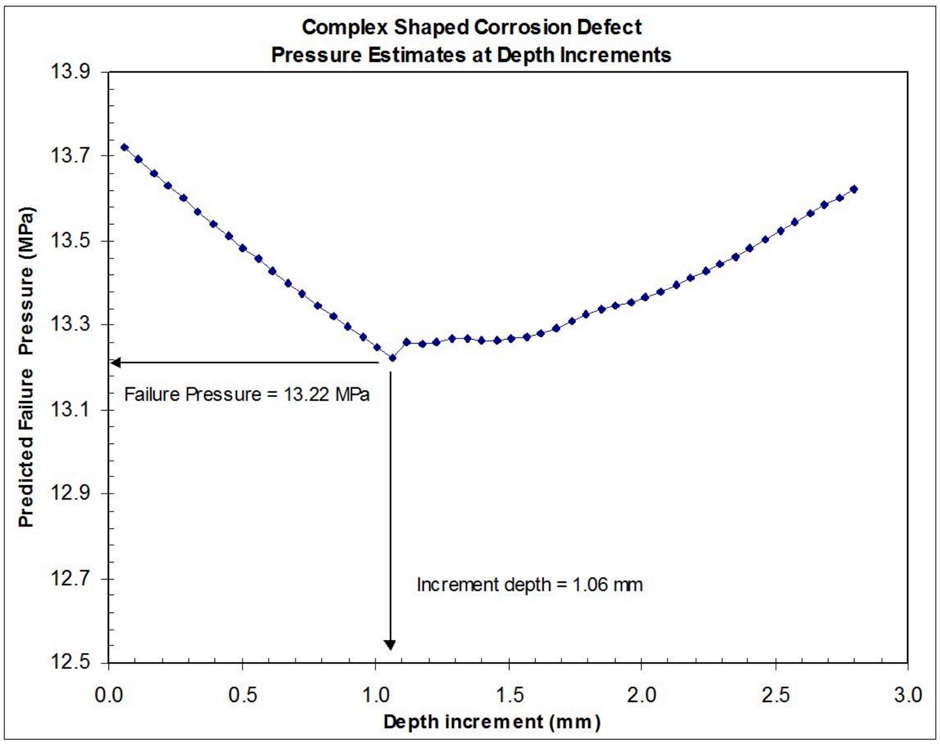

Figure B-4 Variations of the estimated failure pressure for actual corrosion defect - Example assessment

APPENDIX C DETAILED CALCULATION OF MEASUREMENT ACCURACIES

C.1 Implications of correlated and uncorrelated wall loss measurements for the assessment of interacting defects and complex shaped defects

When assessing interacting or complex shaped defects using the methods in Sec.3 (part A) of this document, it is important to establish whether the defect depth measurements are correlated or uncorrelated. The assessment should be made in consultation with an appropriate authority on the measurement technique and procedures used.

The difference between fully correlated measurements and uncorrelated measurements can be explained from the following simple example: two adjacent pits of equal depth. Fully correlated measurements of the depth of two adjacent pits of equal depth would give the same value, because the measurement error would be same. Therefore it would be known that the pits were of equal depth, but the actual depth would not be known with certainty. Uncorrelated measurements of the same two pits may give different values for each pit. If the same uncorrelated measurement technique was applied to many pits of the same depth, then the average value of the depth measurements would give an estimate of the actual depth of the pits.

The difference between fully correlated and uncorrelated measurements of corrosion profiles can be explained in the same way. Fully correlated measurements of the depth at points along a uniform depth wall loss would all be the same, because the measurement error would be the same for each measurement. The technique would reveal a uniform depth wall loss, but the depth would not be known with certainty. An uncorrelated technique would produce different depth estimates at each point, because the error might be different for each individual measurement. For a long defect with a uniform depth profile, if there were a large number of uncorrelated measurements, then the average depth would be accurately measured, but it would not be apparent that the defect had a uniform depth profile.

Depth measurements are averaged as part of the assessment of the interactions between pits and the assessment of complex profiles. Correlated measurements give a larger spread in uncertainty during this process than do uncorrelated measurements. In practice, measurement errors are neither completely uncorrelated nor fully correlated, and it is important to take expert advice to decide which assumption is the most appropriate for a particular inspection technique. If it is not possible to establish whether measurements are correlated or uncorrelated, then the most conservative assumption is to assume that they are fully correlated.

C.2 Partial safety factors for absolute depth measurement (e.g. ultrasonic wall thickness or wall loss measurements)

For known correlation between the pipe wall thickness measurement and the ligament thickness (or corrosion depth) measurements, the following procedure can be used to calculate the StD[d/t] of the relative corrosion depth from the known uncertainties in the absolute measurements. The derivation assumes that d, r and t have LogNormal distributions

C.2.1 Remaining ligament thickness (r) and the wall thickness (t) are measured

$$E[d/t] = 1 - \frac{E[r]}{E[t]}\exp\left(StD[Z_2]^2 - \rho_{Z1Z2}StD[Z_1]StD[Z_2]\right)$$

$$StD[d/t] = E[d/t]\sqrt{\exp\left(StD[Z_1]^2 + StD[Z_2]^2 - 2\rho_{Z1Z2}StD[Z_1]StD[Z_2]\right) - 1}$$

where

Z_1 = ln(r)
Z_2 = ln(t).
The mean value and standard deviation for Z_1 and Z_2 may be derived from:

$$StD\left[Z_1\right] = \sqrt{\ln\left(CoV(r)^2 + 1\right)}$$

$$E\left[Z_1\right] = \ln(E[r]) - 0.5StD\left[Z_1\right]^2$$

$$StD\left[Z_2\right] = \sqrt{\ln\left(CoV(t)^2 + 1\right)}$$

$$E\left[Z_2\right] = \ln(E[t]) - 0.5StD\left[Z_2\right]^2$$

The mean values of the ligament thickness, E[*r*], and the pipe wall thickness, E[*t*], may be approximated by the measured values.

The CoV is the Coefficient of Variation, defined as the standard deviation divided by the mean. The correlation coefficient between Z_1 and Z_2, $\rho_{Z_1Z_2}$, may be calculated from:

$$\rho_{Z_1Z_2} = \frac{E\left[\left(Z_1 - E\left[Z_1\right]\right)\left(Z_2 - E\left[Z_2\right]\right)\right]}{StD\left[Z_1\right]StD\left[Z_2\right]}$$

It should be noted that the correlation between Z_1 and Z_2 is due to the correlation between r and t. If r and t is uncorrelated, then Z_1 and Z_2 is uncorrelated.

C.2.2 Corrosion depth (d) and the wall thickness (t) are measured

$$E[d/t] = \frac{E[d]}{E[t]}\exp\left(StD\left[Z_2\right]^2 - \rho_{Z1Z2}StD\left[Z_1\right]StD\left[Z_2\right]\right)$$

$$StD[d/t] = E[d/t]\sqrt{\exp\left(StD\left[Z_1\right]^2 + StD\left[Z_2\right]^2 - 2\rho_{Z1Z2}StD\left[Z_1\right]StD\left[Z_2\right]\right) - 1}$$

where
Z_1 = ln(d)
Z_2 = ln(t).
The mean value and standard deviation for Z_1 and Z_2 may be derived from:

$$StD\left[Z_1\right] = \sqrt{\ln\left(CoV(d)^2 + 1\right)}$$

$$E\left[Z_1\right] = \ln(E[d]) - 0.5StD\left[Z_1\right]^2$$

$$StD\left[Z_2\right] = \sqrt{\ln\left(CoV(t)^2 + 1\right)}$$

$$E\left[Z_2\right] = \ln(E[t]) - 0.5StD\left[Z_2\right]^2$$

The mean values of the corrosion depth, E[*d*], and the pipe wall thickness, E[*t*], may be approximated by the measured values.

The CoV is the Coefficient of Variation, defined as the standard deviation divided by the mean. The correlation coefficient between Z_1 and Z_2, $\rho_{Z_1 Z_2}$, may be calculated from:

$$\rho_{Z_1 Z_2} = \frac{E\left[\left(Z_1 - E\left[Z_1\right]\right)\left(Z_2 - E\left[Z_2\right]\right)\right]}{StD\left[Z_1\right] StD\left[Z_2\right]}$$

C.3 Application of absolute depth measurement

The acceptance equation require stochastic properties for relative depth measurements. When absolute measurements are available the relative corrosion depth needs to be calculated.

Procedures for calculating the mean and the StD[*d/t*] of the relative corrosion depth from the known uncertainties in the absolute measurements are given below.

C.3.1 If the remaining ligament thickness (r) and the wall thickness (t) are measured:

The acceptance equation is only applicable the when following limitations are fulfilled:

$$StD[l] \leq 20 StD[r]$$

$$StD[t] \leq StD[r]$$

The correlation coefficient is a measure of the mutual linear dependence between a pair of stochastic variables. In most cases, the correlation between the pipe wall thickness measurement and the ligament thickness measurement will not be known and, therefore, it should be assumed to equal zero (i.e. no correlation).

For no correlation, the mean value, E[*d/t*], and the standard deviation, StD[*d/t*], of the relative corrosion depth may be written as:

$$(d/t)_{meas} \equiv E[d/t] \cong \left(1 - \frac{E[r]}{E[t]}\right)$$

$$StD\left[d/t\right] = (1 - E[d/t])\sqrt{\left(CoV(r)^2 + 1\right)\left(CoV(t)^2 + 1\right) - 1}$$

The mean values of the ligament thickness, E[*r*], and the pipe wall thickness, E[*t*], may be approximated by the measured values.

C.3.2 If the corrosion depth (d) and the wall thickness (t) are measured:

The acceptance equation is only applicable when the following limitations are fulfilled:

$$StD[l] \leq 20 StD[d]$$

$$StD[t] \leq StD[d]$$

The correlation coefficient is a measure of the mutual linear dependence between a pair of stochastic variables. In most cases, the correlation between the pipe wall thickness measurement and the metal loss depth measurement will not be known and, therefore, it should be assumed to equal zero (i.e. no correlation).

For no correlation, the mean value, E[*d/t*], and the standard deviation, StD[*d/t*], of the relative corrosion depth may be written as:

$$(d/t)_{meas} \equiv E[d/t] \cong \frac{E[d]}{E[t]}$$

$$StD\left[d/t\right] = E[d/t]\sqrt{\left(CoV(d)^2 + 1\right)\left(CoV(t)^2 + 1\right) - 1}$$

The mean values of the corrosion depth, E[d], and the pipe wall thickness, E[t], may be approximated by the measured values.

APPENDIX D ASSESSMENT OF LONG AXIAL INTERNAL CORROSION DEFECTS

D.1 General

D.1.1 Introduction

This appendix gives specifications to five levels of deliveries from a pipeline in-line UT inspection.

The appendix presents a methodology on how to estimate the pressure resistance of a pipeline containing long axial grooving (the methodology is also applicable for pipelines with other patterns of internal corrosion), and assessment of internal corrosion development with time. The methodology addresses:

— evaluation of inspection results and establishment of a two dimensional representation of the internal corrosion along the pipeline, i.e. river bottom profile ([D.4])
— calculation of pressure resistance accounting for system effect, i.e. integrity assessment “as inspected” ([D.5])
— assessment of internal corrosion development ([D.6]).

A sufficient number of joints should be included in the assessment ensuring that the probability of failure of the system has reached convergence.

The method of generating a remaining wall thickness data set described in [D.4] is well suited to detect and replace unreliable wall thickness readings for internal corrosion defects. However the stand-off data needs to be of good quality. Miss-readings or sudden changes (typically seen at girth welds) in stand-off data will be interpreted as changes in wall thickness. The overall quality of the wall thickness data needs to be reasonable, and heavy echo loss/false readings should be restricted to relatively small and isolated areas.

D.1.2 Levels of delivery from ultrasonic technology inspection

Five levels, as shown in Figure D-1, are presented within this appendix. Level 0 presents the standard delivery from inspection companies, i.e. feature list. The following levels are extended deliveries from inspection companies. [D.2] to [D.6] present specifications of the deliveries of the corresponding levels. Level 1-4 are successive which means that level 2 requires delivery of level 1 etc.

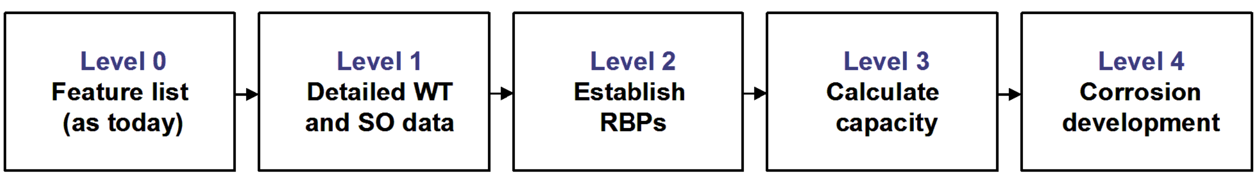

Figure D-1 Overview of the levels of deliveries from ultrasonic inspection (UT)

D.1.3 Definitions

Term	*Definition*
joint	pipe section separated by two girth welds, normally approximately 12m long
pressure resistance	corroded pipe capacity according to DNV-RP-F101 including all relevant design factors

Term	Definition
system effect	DNV-ST-F101 definition: System effects are relevant in cases where many pipe sections are subjected to an invariant loading condition, and potential structural failure may occur in connection with the lowest structural resistance among the pipe sections.

Term	Definition from DNV-ST-F101
system effect	system effects are relevant in cases where many pipe sections are subjected to an invariant loading condition, and potential structural failure may occur in connection with the lowest structural resistance among the pipe sections

D.2 Feature list – level 0

D.2.1 General

This section presents specification of the deliveries from level 0, see Figure D-1.

D.2.2 Quality of inspection results and reporting format

As a minimum the inspection report should include:

— Echo loss reporting:
  — a plot of echo loss along the pipeline
  — percentage echo loss of reported features, i.e. percentage of area given inside the reported length times width, to be given in the feature list
  — distribution of echo loss around the circumference of the pipeline.
— The probability of detection (POD), and the tools limitations.
— The accuracy of depth, length and width measurements with corresponding confidence.
— Possible bias of depth measurements, i.e. measured wall thickness of assumed un-corroded area:
  — the un-corroded wall thickness in the WT data should be close to nominal wall thickness
  — if available, un-corroded area should be compared to previous inspections.
— Threshold values for depth, length and width measurements.
— A figure to show how the features are reported, see example in Figure D-2:
  — deepest point
  — start point
  — point(s) to which length, width and orientation is referred.

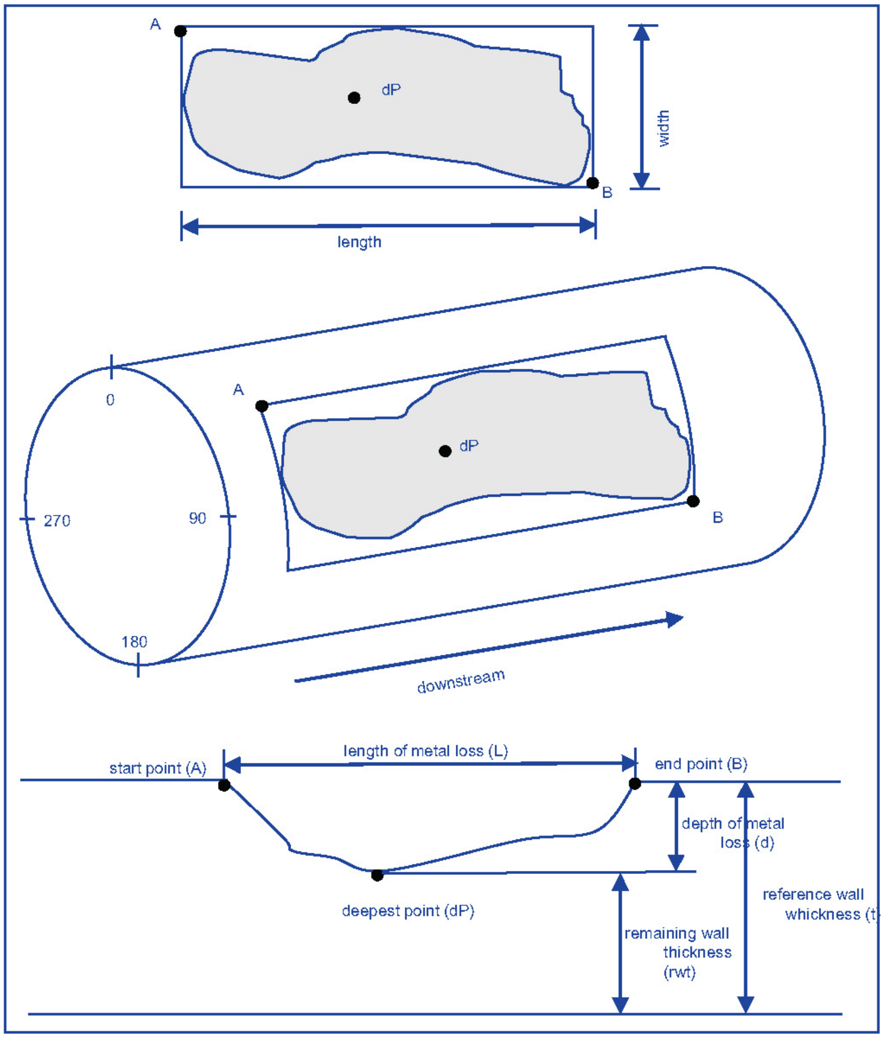

Figure D-2 Location and dimension of metal loss features

D.3 Detailed WT and SO data – level 1

D.3.1 General

This section presents specification of the deliveries from level 1, see Figure D-1.

D.3.2 Specification of WT and SO data

The detailed *WT* and *SO* data should include the following:

— Detailed WT and SO data should as a minimum be given for the entire joint, i.e. for the entire length and for the entire circumference of the joint.
— The WT and SO data should be corresponding in the axial and circumferential direction.

— The detailed data should be reported in the following format:

  — First row reserved for information (i.e. inspection ID, time etc.).
  — Second row should give the degree position in the circumferential direction.
  — First column should give the odometer distance of the pipeline.

The format of the file should be csv files. An example of format of a *WT* file is given in Figure D-3.

An additional delivery should be an index file containing the following information of the *WT* and *SO* data:

— Start and end odometer distance of the joint.
— Name of file containing the WT and SO data respectively.
— The rank of the joint with respect to capacity; preferable according to calculated capacity, secondly according to defect size.

Joint 1000 SurveyID S100

Odometer	0°	1.9°	3.8°	5.6°	7.5°	9.4°	...	346.9°	348.8°	350.6°	352.5°	354.4°	356.3°	358.1°
5000.000	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.003	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.006	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.009	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.012	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.015	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.018	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.021	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.024	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.027	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.030	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.033	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.036	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.039	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5000.042	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
5012.750	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.747	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.744	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.741	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.738	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.735	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.732	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.729	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.726	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.723	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.720	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.717	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.714	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.711	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.708	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.705	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.702	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.699	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.696	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.693	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.690	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.687	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.684	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.681	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.678	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.675	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.672	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.669	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.666	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1
5012.663	12.1	12.1	12.1	12.1	12.1	12.1	...	12.1	12.1	12.1	12.1	12.1	12.1	12.1

Figure D-3 Example of WT file

D.4 Establish river bottom profile – level 2

D.4.1 General

This section presents specification of the deliveries from level 2, see Figure D-1.

The following method is well suited to detect and replace unreliable wall thickness readings for internal corrosion defects. However:

— The stand-off data needs to generally be of good quality. Miss-readings or sudden changes (typically seen at girth welds) in stand-off data will be interpreted as changes in wall thickness.
— The overall quality of the wall thickness data needs to be reasonable, with heavy echo loss/false readings restricted to relatively small and isolated areas.

D.4.2 Establish RWT_{SO} data based on WT and SO data

To establish the RWT_{SO} data set, a reference matrix *WTSO* is established. The sum of a *WT(i,j)* and the corresponding *SO(i,j)* gives the distance from the sensor to the outer wall of the pipeline (*i* indicating each longitudinal measurement point and j indicating each sensor at the corresponding circumferential plane/sector). This reference, called *WTSO*, should ideally be constant for each sensor (see Figure D-4). Contributions to variations in the *WTSO* for each column are wall thickness variations (on the outside of the pipeline), measurement uncertainty, vibrations/radial movement of the tool/sensor, and erroneous or missing data points.

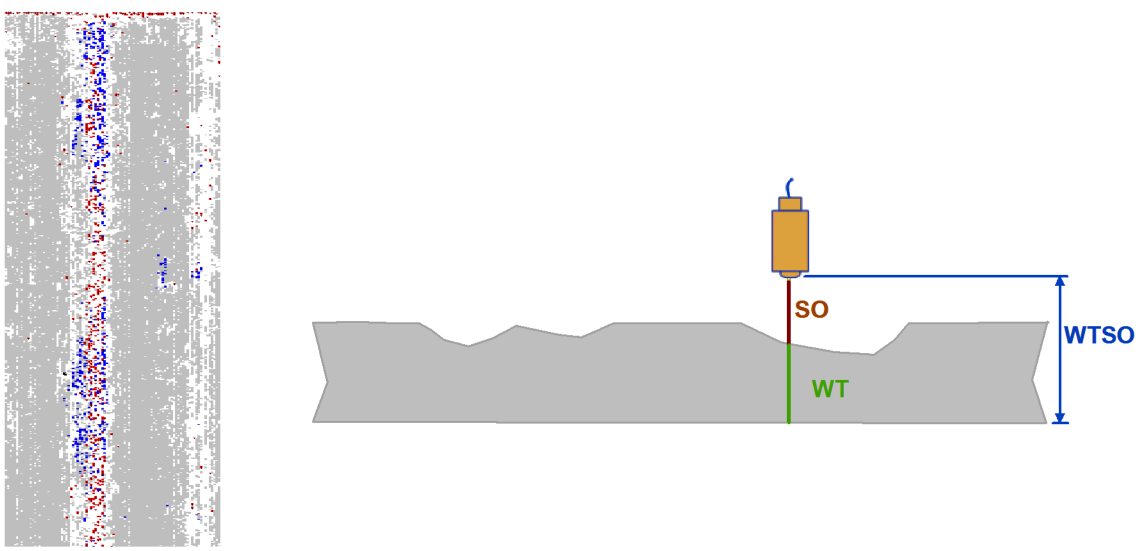

Figure D-4 *WTSO* based on *SO* and *WT* measurements along one probe (black vertical line)*

* Color scheme of inspection result plot:

— grey: WT larger than Nominal WT
— blue: WT less than Nominal WT larger than the fabrication tolerance (approx 90% of WT)
— yellow: WT larger than 80% of the WT
— red: WT less than 80% of the WT
— white: missing data.

The median of each column (sensor) of the *WTSO* data is established as a reference value for each sensor along the joint, denoted $WTSO_{joint\ ref}(j)$. Using the same method, reference values are established for *l* shorter sections, denoted $WTSO_{section\ ref}(j,l)$. The section length is chosen so that the inspection tool will not penetrate into defects shorter than this length. A section length of 250 mm is recommended for most cases*. This process is repeated for *SO* data to establish $SO_{joint\ ref}(j)$ and $SO_{section\ ref}(j)$. $WTSO_{ref}(j)$ and $SO_{ref}(j)$ is then chosen for each column as either $WTSO_{joint\ ref}(j)$ and $So_{joint\ ref}(j)$or $WTSO_{section\ ref}(j)$ and $SO_{section\ ref}(j)$ depending on which combinations allows for the lowest WT values to be accepted. Elements, *WTSO(i,j)*, within column *j* which deviate significantly from the reference value $WTSO_{ref}(j)$ are considered erroneous data. The *WTSO(i,j)* is allowed to vary within ± the 99% upper quantile of the measurement uncertainty together with half the fabrication tolerance (as only "outside" variations will influence the *WTSO* values). This variation is denoted "allowable *WTSO* variation" (*av*).

* For cases were the *WT* data are unreliable in larger coherent sections (or girth welds), the method may underestimate the remaining wall thickness. The section length can in these cases be adjusted (to be longer), however one has to verify that this does not result in non-conservative results due to inspection tool penetrating defects shorter than the chosen length.

The reference value $WTSO_{ref}(j)$ for column j may for some sensors be dominated by erroneous data, e.g. high echo loss in the *WT*() along the entire section. To accommodate for this, the reference value is not allowed to deviate from the minimum and maximum of the *N* neighbouring columns more than the allowable *WTSO* variation, *av*. If the reference value is outside this range, it will be set to the lower or upper bound respectively. A neighbouring size of *N* = 7 is recommended as this gives 3 sensors on either side of the sensor in question.

Generally, where the *WTSO(i,j)* is within the allowable range, the original *WT(i,j)* value is reproduced in $RWT_{SO}(i,j)$ by:

$$RWT_{so}(i,j) = WTSO(i,j) - SO(i,j) = WT(i,j) \tag{D-1}$$

If the *WT(i,j)* is missing, or possibly erroneous, the *WTSO(i,j)* will be missing or outside the limits of acceptable variation (see algorithm in [D.4.2.1]), If the *WTSO(i,j)* is not accepted the *RWT(i,j)* should be estimated based on the median of *WTSO* data for a given length (±k/2 elements around the relevant element), and the *SO(i,j)* data point (equation (D-2) and (D-3)). It is desirable to have the length, *k*, as short as possible, but with sufficient points to give a representative median value. A length of approximately 150 mm is recommended (which will give approximately 50-75 measurepoints of which the median is taken).

$$movWTSO_{median}(i,j) = Median(WTSO(i-k/2,j){:}WTSO(i+k/2,j)) \tag{D-2}$$

$$RWT_{so}(i,j) = mowWTSO_{median}(i,j) - SO(i,j) \tag{D-3}$$

The $movWTSO_{median}(i,j)$ should be within the same limits around the reference value as above. Additional checks are performed as some $movWTSO_{median}(i,j)$ values outside the given range are still acceptable ([D.4.2.1]). If the value is not acceptable the $RWT_{SO}(i,j)$ will be estimated based on *SO(i,j)* and the previous *WTSO* value, or the *lower* or *upper* bound depending on the value of $movWTSO_{median}(i,j)$. See algorithm in [D.4.2.1] for details.

D.4.2.1 Algorithm for estimating remaining wall thickness based on WT and SO data

Input: Two arrays of wall thickness and stand-off data (denoted $WT()$ and $SO()$ respectively).

Upper and lower circumferential limit

Allowable $WTSO$ variation, av

Neighbourhood size, N

Step 1: Sort and filter out chosen circumferential sector of *WT*() and *SO*()

\\Sort the columns of $WT()$ and $SO()$ with ascending circumferential position (degrees around the pipeline). Then filter out the sector of the pipeline from degree – to degree that is of interest. $FromDeg<ToDeg$, and $FromDeg$, $ToDeg \in [0,360]$.\\

Step 2: Matrix addition of *WT*() and *SO*() to get *WTSO*()

\\For each element i,j in $WT()$ and $SO()$ add the elements to create a data set of the sums, $WTSO()$.\\

For each row i

For each column j

$$WTSO(i,j) = WT(i,j) + SO(i,j)$$

Step 3: Find reference value ($WTSO_{joint\ ref}()$) for each column in *WTSO*()

\\Assume that within the first N columns, at least one column has sufficient $WTSO$ data to establish a reliable reference. For each column $j \leq N$, calculate the median of the values within the column, $TmpWTSO_{median}(j)$. The maximum of the $TmpWTSO_{median}(j \leq N)$ can be assumed to be a reliable first reference value. Set temporary lower and upper bound on acceptable $TmpWTSO_{median}()$ values to the maximum value ± the allowable $WTSO$ variation, av.\\

For each column $j \leq N$

$$TmpWTSO_{median}(j) = \text{Median}(WTSO(:,j))$$

$$TmpWTSO_{LB} = \text{Maximum}(TmpWTSO_{median}()) - av$$

$$TmpWTSO_{UB} = \text{Maximum}(TmpWTSO_{median}()) + av$$

\\Remove $TmpWTSO_{median}()$ values outside the acceptable range and replace it using the ConservativeSmooth algorithm.\\

For each column $j \leq N$

If $TmpWTSO_{median}(j) < TmpWTSO_{LB}$ **Or** $TmpWTSO_{median}(j) > TmpWTSO_{UB}$ **Then**

$$TmpWTSO_{median}(j) = \text{ConservativeSmooth}(TmpWTSO_{median}(), j, N)$$

\\Set new lower and upper bounds on acceptable $TmpWTSO_{median}()$ values as the minimum and maximum of $TmpWTSO_{median}()$ (from the first N columns) ± the allowable $WTSO$ variation, av.\\

$$TmpWTSO_{LB} = \text{Minimum}(TmpWTSO_{median}()) - av$$

$$TmpWTSO_{UB} = \text{Maximum}(TmpWTSO_{median}()) + av$$

\\For each column, j, use the established lower and upper bounds on acceptable $TmpWTSO_{median}(j)$ values to establish the reference value $WTSO_{joint\ ref}(j)$. Then update the temporary lower and upper bounds.\\

For each column j in $WTSO()$

\\For column $j - N/2$ to $j + N/2$, calculate the $TmpWTSO_{\text{median}}()$ being the median of the values within the temporary lower and upper bounds ($TmpWTSO_{\text{LB/UB}}$) of each of the N columns. If $TmpWTSO_{\text{median}}(j)$ is empty (not enough values within the acceptable range), it will be estimated by the ConservativeSmooth algorithm (see Sec.D.4.2.2) based on the median of **all** the values within column j.\\

For each column $j - N/2$ to $j + N/2$

$TmpWTSO_{\text{median}}(j) = \text{Median}(WTSO(:,j), TmpWTSO_{\text{LB}}, TmpWTSO_{\text{UB}})$

If Not $TmpWTSO_{\text{median}}(j) \in [TmpWTSO_{\text{LB}}, TmpWTSO_{\text{UB}}]$ **Then**

\\Recalculate $TmpWTSO_{\text{median}}(j)$ for column j being the median of **all** the values (except empty) in the current column.\\

$TmpWTSO_{\text{median}}(j) = \text{Median}(WTSO(:,j))$

$TmpWTSO_{\text{median}}(j) = \text{ConservativeSmooth}(TmpWTSO_{\text{median}}(), j, \text{N})$

\\Set the reference value for the column equal to the temporary median.\\

$WTSO_{\text{joint ref}}(j) = TmpWTSO_{\text{median}}(j)$

\\Set new lower and upper bounds on acceptable $TmpWTSO_{\text{median}}()$ values as the minimum and maximum of $TmpWTSO_{\text{median}}()$ (from the neighbouring columns $j - N/2$ to $j + N/2$) ± the allowable $WTSO$ variation, av.\\

$TmpWTSO_{\text{LB}} = \text{Minimum}(TmpWTSO_{\text{median}}()) - av$

$TmpWTSO_{\text{UB}} = \text{Maximum}(TmpWTSO_{\text{median}}()) + av$

Step 4: Do Step 3 for $SO()$ to establish $SO_{\text{joint ref}}()$

Step 5: Repeat step 3 and 4 for each section l (250 mm) to establish $WTSO_{\text{section ref}}()$ and $SO_{\text{section ref}}()$

Step 6: Calculate moving $WTSO_{\text{median}}()$ and $SO_{\text{median}}()$

\\For each element $WTSO(i,j)$ calculate the median of $WTSO()$ for the k elements around row element i, where k is the number of elements within the specified section length.\\

For each column j

For each row i

$movWTSO_{\text{median}}(i,j) = \text{Median}(WTSO(i\text{-}k/2,j) : WTSO(i+k/2,j))$

$movSO_{\text{median}}(i,j) = \text{Median}(SO(i\text{-}k/2,j) : SO(i+k/2,j))$

Step 7: Calculate remaining wall thickness (RWT_{SO})

\\For each element $WTSO(i,j)$ calculate the $RWT(i,j)$.\\

For each section l

For each column j

If $WTSO_{\text{joint ref}}(j) - SO_{\text{joint ref}}(j) < WTSO_{\text{section ref}}(j,l) - SO_{\text{section ref}}(j,l)$ **Then**

$WTSO_{\text{ref}}(j,l) = WTSO_{\text{joint ref}}(j)$

$SO_{\text{ref}}(j,l) = SO_{\text{joint ref}}(j)$

Else

$WTSO_{\text{ref}}(j,l) = WTSO_{\text{section ref}}(j,l)$

$SO_{\text{ref}}(j,l) = SO_{\text{section ref}}(j)$

For each row i within section l

If $WTSO(i,j) \in [WTSO_{\text{ref}}(j,l) - av, WTSO_{\text{ref}}(j,l) + av]$ **And** $SO(i,j) \in [SO_{\text{ref}}(j,l) - av, SO_{\text{ref}}(j,l) + av]$ **Then**

Believe in WT

Else

\\Calculate the difference between $WTSO_{\text{ref}}(j)$ and $SO_{\text{ref}}(j)$ and the difference between the moving median of *WTSO* and *SO*.\\

$TmpColRefDiff = WTSO_{\text{ref}}(j,l) - SO_{\text{ref}}(j,l)$

$TmpMovingDiff = movWTSO_{\text{median}}(i,j) - movSO_{\text{median}}(i,j)$

If *Abs*(TmpColRefDiff – *TmpMovingDiff*) < *av* **Then**

\\Believe in moving *WTSO* and *SO*.\\

If $WTSO(i,j) \in [movWTSO_{\text{median}}(i,j) - av, movWTSO_{\text{median}}(i,j) + av]$ **Then**

Believe in WT

Else

Estimate RWT from moving WTSO

Else

If $movWTSO_{\text{median}}(i,j) < WTSO_{\text{ref}}(j) - av$ **Then**

\\Don't believe in moving *WTSO*.\\

If *i* is 1 **Then**

Estimate RWT from $WTSO_{ref}$

Else

Estimate RWT from Previous

Else if $movWTSO_{\text{median}}(i,j) > WTSO_{\text{ref}}(j,l) + av$ **Then**

\\Believe in moving *WTSO* if also moving *SO* shows an increase and the difference between the moving *WTSO* and *SO* is less than the reference difference (*SO* is closer to *WTSO* than the reference, indicating corrosion).\\

If $movSO_{\text{median}}(i,j) > SO_{\text{ref}}(j,l) + av$ **And** $TmpMovingDiff < TmpColRefDiff + av$ **Then**

\\Believe in moving *WTSO*.\\

If $WTSO(i,j) \in [movWTSO_{\text{median}}(i,j) - av, movWTSO_{\text{median}}(i,j) + av]$ **Then**

Believe in WT

Else

Estimate RWT from moving WTSO

Else

\\Don't believe in moving *WTSO*.\\

Estimate RWT from $WTSO_{ref}$

Else

\\Believe in moving *WTSO*.\\

If $WTSO(i,j) \in [movWTSO_{\text{median}}(i,j) - av, movWTSO_{\text{median}}(i,j) + av]$ **Then**

Believe in WT

Else

Estimate RWT from moving WTSO

\\Calculate remaining wall thickness ($RWT_{SO}(i,j)$).\\

If *SO* is missing **Then**

\\$RWT_{SO}(i,j)$ does not get a value\\

Else if *Believe in WT* **Then**

\\Use original $WT(i,j)$\\

$RWT_{SO}(i,j) = WTSO(i,j) - SO(i,j)$

Else if *Estimate RWT from moving WTSO* **Then**

\\Estimate R*WT* from moving *WTSO* median\\

$RWT_{SO}(i,j) = movWTSO_{\text{median}}(i,j) - SO(i,j)$

Else

\\Don't believe in *WT* or moving *WTSO*. Estimate *WT* from $WTSO_{\text{ref}}$ or *Previous*.\\

If *Estimate RWT from* $WTSO_{ref}$ **Then**

$RWT_{SO}(i,j) = WTSO_{\text{ref}}(j,l) - SO(i,j)$

Else if *Estimate RWT from Previous* **Then**

$RWT_{SO}(i,j) = RWT(i-1,j) + SO(i-1,j) - SO(i,j)$

Output: One array of remaining wall thickness, $RWT_{SO}()$.

D.4.2.2 Algorithm for conservative smooth

Input: One matrix of neighbouring data, *InputM*()
Row and column index (i,j) for data point which are going to be compared against its neighbours with the conservative smooth algorithm
Neighbourhood size N

Step 1 Calculate Conservative smooth value for data point (i,j)

k=3

Do while $k < N$

min = Minimum[$InputM(i - k/2, j - k/2)$: $InputM(i + k/2, j + k/2)$], excluding $InputM(i,j)$

max = Maximum[$InputM(i - k/2, j - k/2)$: $InputM(i + k/2, j + k/2)$] , excluding $InputM(i,j)$

If $InputM(i,j)$ >= min and $InputM(i,j)$ <= max **Then**

$CS = InputM(i,j)$

Exit loop

Else

If $InputM(i,j)$ > max **Then**

$CS = max$

Else

$InputM(i,j) = min$

k = k+2

Output: Conservative smooth, CS

D.4.3 River bottom profile per joint

In order to get an overview of the corrosion depth along the joint and for a selected width, a river bottom profile (*RBP*) can be established. These *RBP*s are two dimensional representations of the remaining wall thickness along the pipeline joint, i.e. a projection of the minimum values across the circumferential width. An algorithm has been developed to produce the *RBP*s based on the RWT_{SO} data, see below.

D.4.3.1 Algorithm to produce RBPs based on RWTSO data

Input: One array of remaining wall thickness, $RWT_{SO}()$

Step 1: Find *RBP*(*i*) value based on the $RWT_{SO}(i,:)$ values

For each row i in the $RWT_{SO}()$

\\Calculate the *RBP* value for the corresponding position along the pipeline.\\

For each element j in $RWT_{SO}(i,:)$

\\If $RWT_{SO}(i,j)$ and the consecutive element are empty, a temporary value representative for $RWT_{SO}(i,j)$ is the average of nearby values that are not empty. Check if the value is less than the previous minimum value.\\

If $RWT_{SO}(i,j)$ is empty **Then**

\\Check if next element $RWT_{SO}(i,j+1)$ is empty.\\

If $RWT_{SO}(i,j+1)$ is empty **Then**

\\ Find average of the nearby values in $RWT_{SO}()$ from i-1 to i+1 and j-1 to j+1, $tmpRWT_{ij}$.\\

$tmpRWT_{ij}$ = Average[$RWT_{SO}(i - k/2, j - k/2)$: $RWT_{SO}(i + k/2, j + k/2)$]

	j-1	j	j+1
i-1	**15.2**		**15.1**
i	**14.5**		
i+1		**14.6**	**15.3**

If $tmpRWT_{ij}$ is empty **Then**

\\Exit the loop and set *RBP*(*i*) to empty.\\

continue with next row i

Else if $tmpRWT_{ij}$ < previous minimum value **Then**

\\Set $tmpRWT_{ij}$ as the minimum value.\\

$RBP(i) = tmpRWT_{ij}$

Else continue with next element j

Else if $RWT_{SO}(i,j)$ < previous minimum value (*RBP*(*i*)) **Then**

\\Set $RWT_{SO}(i,j)$ as the minimum value.\\

$RBP(i) = RWT_{SO}(i,j)$

\\If a 3 by 3 area of measured points are empty around one or more elements on row i, *RBP*(*i*) will be empty.\\

Output: An array, *RBP*(), with the river bottom profile values and the corresponding relative length/position along the pipeline joint, see Figure D-5.

```
#------------------------------
#River Bottom Profile
#Input parameters
#------------------------------
WTSOPath                C:\...
WTSOPrefix              Critical_defect
JointID                 1000
SurveyID                S100
SurveyDate              01.01.2008
NominalWT (mm)          12
OuterDiameter (mm)      200
OdoStart (m)            5000
OdoEnd (m)              5012.663
DegFrom                 0
DegTo                   360
RWTTresholdMin (mm)     12
RWTTresholdMax (mm)     20
#------------------------------
#Profiles
#------------------------------
Distance (m)            RBP
                0.000   11.156
                0.003   10.880
                0.006    9.875
                0.009    9.920
                0.012    9.420
                0.015    9.400
                0.018    9.525
                0.021    9.550
                0.024    9.560
                0.027    9.267
                0.030    9.629
                0.033   10.075
                0.036   10.540
                0.039   10.000
                0.042    9.822
                    .        .
                    .        .
                    .        .
                12.75    8.634
               12.747    9.000
               12.744   10.200
               12.741   10.800
               12.738   10.800
               12.735   12.000
               12.732   12.400
               12.729    9.000
               12.726   12.400
               12.723   12.400
                12.72   12.025
               12.717   11.800
               12.714   12.047
               12.711    9.800
               12.708    9.200
               12.705   10.000
               12.702    9.600
               12.699    9.400
               12.696    9.000
               12.693    8.673
                12.69    9.716
               12.687    8.600
               12.684    9.077
               12.681   10.039
               12.678   10.200
               12.675    9.000
               12.672    9.227
               12.669   12.400
               12.666   12.458
               12.663   12.025
#EOF--------------------------
```

Figure D-5 Example of RBP file

D.5 Calculate capacity – level 3

D.5.1 General

This section presents specification of the deliveries from level 3, see Figure D-1.

In Figure D-6 the methodology of the capacity calculation is illustrated. Inputs to the calculations are RBPs as established according to [D.4]. Details of the methodology are given in the following sections.

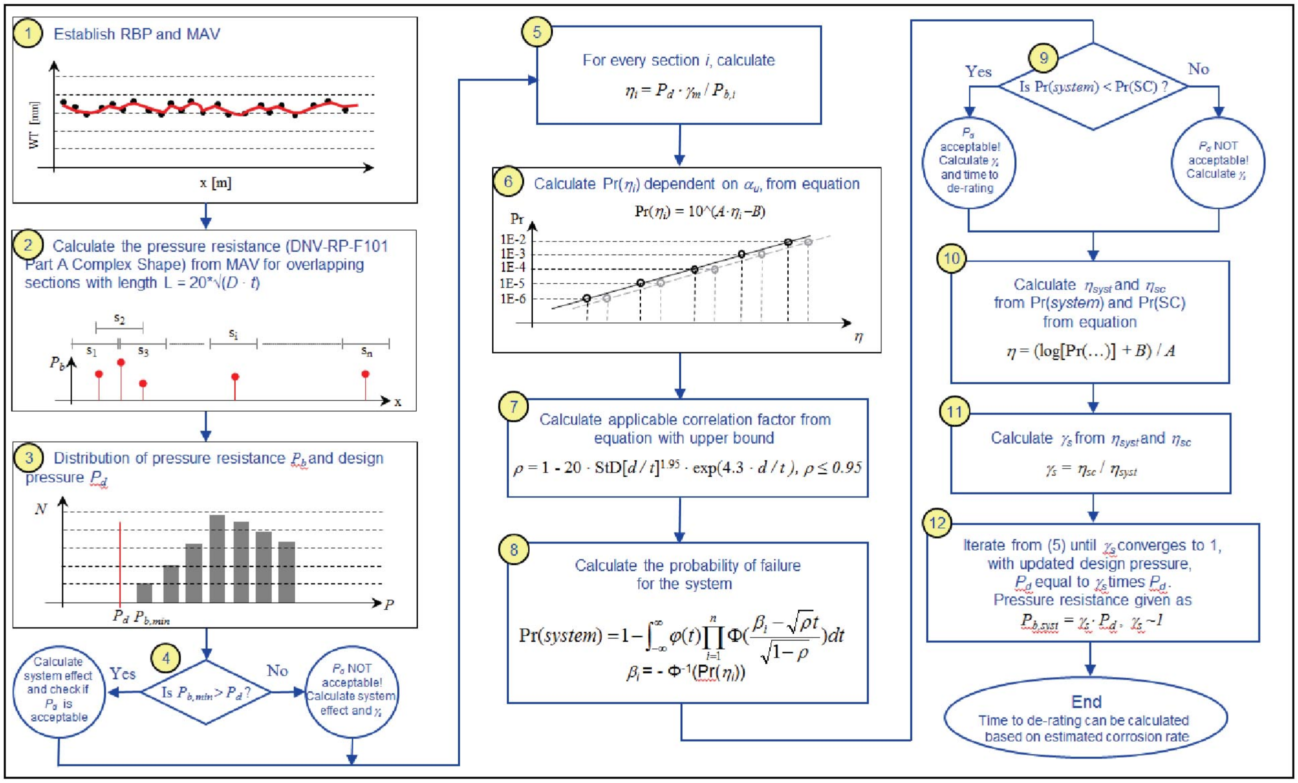

Figure D-6 Assessment flow diagram

In general, referring to Figure D-6 above, the methodology consists of calculating the pressure resistance according to the Complex Shaped Defect methodology in [3.9]. The pressure resistance is calculated from moving average profiles (*MAV*) established from the *RBP*s (1) for sections of the pipeline of a given length (2). Further, a relation between the pressure resistance and probability of failure (PoF) is established (6), the correlation factor is calculated (7) and based on the individual sections the total system PoF for the pipeline is estimated (8). The total system PoF for the pipeline is compared to the acceptable PoF for the given Safety Class, /8/ (9), and a pressure adjustment factor is estimated (11) in order to calculate the system capacity of the pipeline (12). The pressure resistance of the pipeline is then given by the design pressure times the pressure adjustment factor. Details of the procedure are given below.

D.5.2 Burst capacity of pipeline including system effect

D.5.2.1 Complex shape capacity

A moving average profile (MAV) is calculated from the *RBP*s to smooth the profile, see (1) of Figure D-6. The value at one location is the average over a specified length, see illustration in Figure D-9. The *RBP* is averaged over a length of $k \cdot \sqrt{D \cdot t}$, where k = 0.5. Data points which are significantly lower than its neighbours within this length do not affect the capacity as can be seen in Figure D-7.

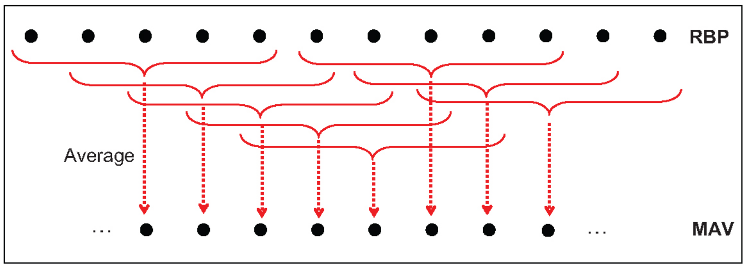

Figure D-7 Illustration of calculation of moving average (MAV) profile

The pressure resistance of sections of length $k \cdot \sqrt{D \cdot t}$, for k = 20, is calculated according to [3.9]. From this defect length, increasing the length will not decrease the allowable defect depth significantly, see Figure D-8. The capacity is calculated from the *MAV* profiles established from the *RBP*s. In order to make sure that the most unfavourable combination of defect shapes are included, the capacity is calculated for overlapping sections. The capacity of each section is taken as the lowest of the overlapping capacities. A histogram of the calculated pressure resistances for all sections is a good illustration of the distribution of the capacity of the joints considered, see (2) and (3) of Figure D-6.

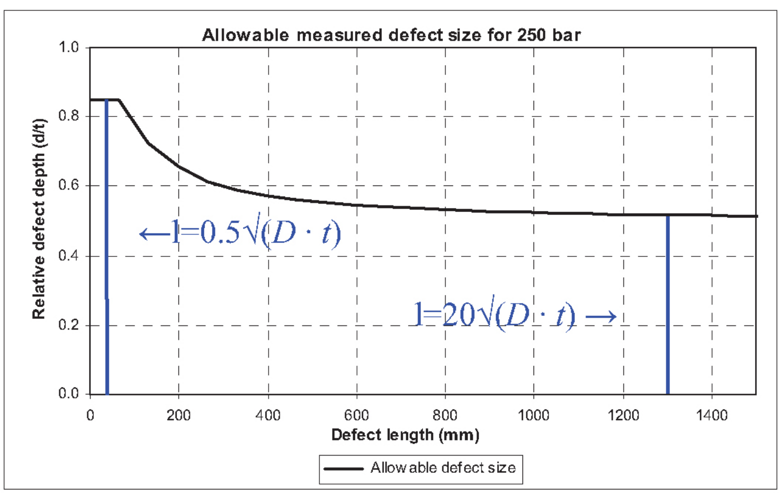

Figure D-8 Example of allowable measured defect size, single defect methodology

D.5.2.2 Probability of failure versus pressure resistance

The pressure resistance for pipelines with a corrosion defect, given by the burst capacity equation with safety factors is shown in [3.7.3.1].

In Table 3-2, γ_m is given for safety class *Low, Medium, High and Very High*, see Table D-1. Note that the methodology in this report is valid for absolute measurements only, i.e. UT inspections.

Table D-1 Partial safety factor for model prediction gm for absolute depth measurements

Inspection method	*Safety class*			
	Low	*Medium*	*High*	*Very high*
Absolute (e.g. UT)	γ_m = 0.94	γ_m = 0.88	γ_m = 0.82	γ_m = 0.77

The calculated burst capacity of the equation in [3.7.3.1] corresponds to a PoF through the following equation:

$$Pr(\eta) = 10 \wedge (A \cdot \eta - B) \qquad \text{(D-1)}$$

where $\eta = \gamma_{inc} \cdot P_d \cdot \gamma_m / P_b$. Hence based on the Complex Shape capacity calculated for every section, $P_{b,i}$, the corresponding PoF, $Pr(\eta_i)$, is calculated from equation (D-1) for the given Safety Class and design pressure, P_d.

The *A* and *B* factors are given in Table D-2.

Table D-2 Regression coefficients for relation between Pr(η) and η

	A	*B*
Regression coefficients	16.6	18.6

D.5.2.3 System effect

The calibration of the partial safety factors in [3.3] is based on one single defect, or a limited corroded area. It is based on the assumption that the geometry of the defect or corroded area dominates the capacity calculation and thus the probability of failure for the pipeline.

The pipeline is subjected to an "invariant" load from the pressure. If the pipeline has a river bottom corrosion over a substantial length, the pipeline will have many pipe sections where the probability of a combination of low nominal wall thickness and material strength in the same area as deep corrosion is higher than for a single corrosion defect. The pipeline is then experiencing a system effect. The system effect needs to be considered for pipelines with this type of corrosion in order to be aligned with the safety philosophy of the standard DNV-ST-F101, /8/. The probability of failure for the entire pipeline, Pr(*system*), shall satisfy the target PoF level according to the given Safety Class.

D.5.2.4 Correlation

The correlation between different sections of a pipeline might have a significant impact on the total system probability, Pr(*system*). The two extreme cases are independent sections (correlation $\rho = 0$) and fully correlated sections (correlation $\rho = 1$), which show the importance of the correlation factor. For independent sections, Pr(*system*) is approximately equal to the sum of each section's PoF ($Pr(\eta_i)$) which for a long pipeline with short calculation sections can grow quite large. For fully correlated sections Pr(*system*) is equal to the section with the highest PoF, i.e. Pr(*system*) is controlled by the worst section.

The correlation factor is dependent on the *d/t* ratio and the standard deviation of *d/t*, which is given by the inspection accuracy. The correlation factor can be found from the following equation

$$\rho = 1 - 20 \cdot StD[d/t]^{1.95} \cdot \exp(4.3 \cdot d/t)\,, \rho \leq 0.95 \qquad \text{(D-4)}$$

, $\rho \leq 0.95$

where standard deviation of *d/t*, StD[*d/t*], is given in [3.3]. A conservative d would be to use the deepest reported depth. The correlation is however dependent on the collection of deepest points, and it would be more realistic to base it on a characteristic depth (i.e. the average of the 1/3 deepest reported depths of the selected joints).

For a given correlation factor (r) the system probability of failure, Pr(*system*) is given by the following relation, /19/.

$$\Pr(system) = 1 - \int_{-\infty}^{\infty} \varphi(t) \prod_{i=1}^{n} \Phi\left(\frac{\beta_i - \sqrt{\rho}t}{\sqrt{1-\rho}}\right) dt \quad \text{(D-5)}$$

$$\beta_i = -\Phi^{-1}(\Pr(\eta_i)) \quad \text{(D-6)}$$

where β_i and $\Pr(\eta_i)$ are the reliability index and PoF for section *i*, and *n* is the number of sections considered. Φ is the cumulative standard normal distribution and φ is the standard normal distribution. The equation is valid for $\rho \in [0, 1]$.

D.5.2.5 Selection of representative joints

When substantial lengths of a pipeline have experienced this type of channelling corrosion, it is common practice to report a selection of the "worst" joints in the pipeline assuming that these defects are representative with respect to the capacity of the pipeline. The selection of "worst" joints is usually ranked based on the size (primarily depth) of the reported defects. However, this may not correspond to the worst joints with respect to capacity, as a short and deep defect may have a higher capacity than a slightly less deep but longer defect, see Figure D-8.

A histogram of the PoF for each joint based on the sorting of the reported list, together with the cumulative PoF, is a good illustration to confirm if a sufficient number of joints have been included in the assessment, (Figure D-9). If the cumulative PoF converges it indicates that including more joints will have a negligible contribution to the total PoF. Thus the assessment based on the selected "worst" joints can be representative for the entire pipeline. However, one should note that where the corrosion is more even for a larger part of the pipeline, this method of ranking might not single out the worst joints with respect to capacity. Note that this is only a check that enough joints have been included in the analyses and no system effect is considered. The capacity and PoF is estimated for the worst joints and this PoF is added up as more joints are included. If the system effect is included this should make the convergence go faster.

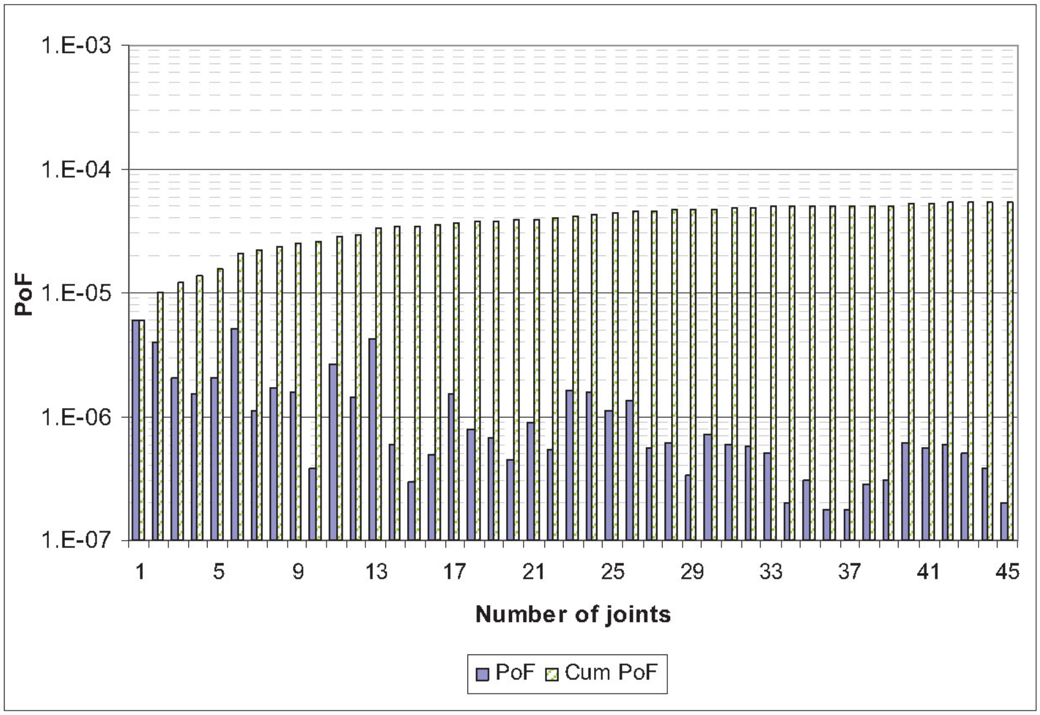

Figure D-9 Probability of failure for joints sorted with respect to defect depth

D.5.2.6 Pressure resistance including system effect

In order to estimate the pressure resistance of the pipeline including system effect, Pb,syst, the inverse of equation (D-1) is applied to calculate hsyst based on Pr(system) where A and B are given in Table D-2, i.e.

$$\eta_{syst} = (\log_{10}(\Pr(system)) + B) / A \qquad \text{(D-7)}$$

which gives the pressure adjustment factor, γ_s

$$\gamma_s = \gamma_m / \eta_{syst} \qquad \text{(D-8)}$$

to be applied to the design pressure. The pressure resistance is estimated as an iteration process by changing the input "design pressure" at the beginning of the assessment ([D.5.2.2]) until the pressure adjustment factor, γ_s, converges to 1.

A pressure adjustment factor $\gamma_s \sim 1$ corresponds to the pressure resistance including system effect, given as γ_s times the "design pressure" included in the last iteration.

$$P_{b,syst} = \gamma_s \cdot \gamma_{inc} \cdot P_d \qquad \text{(D-9)}$$

D.5.2.7 Algorithm for pressure resistance of pipeline including system effect

Input:_MAV_ profiles for all joints considered

Step 1: Calculate Complex Shape capacity for each section

\\For every section i of the pipeline joints, calculate the capacity according to [3.9].\\

For each section i

calculate $P_{b,i}$ according to [3.9].

Step 2: Calculate probability of failure for each section

\\For every section i of the pipeline joints, calculate η_i and thereof probability of failure Pr(η_i), where A and B are given in Table D-2.\\

For each section i

$\eta_i = P_d \cdot \gamma_{inc} \cdot \gamma_m \,/\, P_{b,i}$

$\Pr(\eta_i) = 10\hat{}(A \cdot \eta_i - B)$

Step 3: Calculate system correlation factor

\\Based on the accuracy of the internal inspection, calculate the standard deviation of the d/t ratio, StD[d/t], according to Sec. 3.3. Based on a characteristic depth of the corrosion in the pipeline, calculated the correlation factor, ρ.\\

$$\rho = 1 - 20 \cdot StD[d/t]^2 \cdot \exp(4.3 \cdot d/t),\ \rho \le 0.95$$

Step 4: Calculate system probability of failure

\\For every section i of the pipeline joints, calculate the reliability index, β_i. Calculate the system probability of failure, Pr($system$), based on the correlation factor, ρ. Φ is the cumulative standard normal distribution (can be calculated by the excel function =NORMDIST("expression"; 0; 1; TRUE)) and φ is the standard normal distribution (can be calculated by the excel function =NORMDIST(t; 0; 1; FALSE)). \\

For each section i

$$\beta_i = -\,\Phi^{-1}(\Pr(\eta_i))$$

$$\Pr(system) = 1 - \int_{-\infty}^{\infty} \varphi(t) \prod_{i=1}^{n} \Phi\left(\frac{\beta_i - \sqrt{\rho}t}{\sqrt{1-\rho}}\right) dt$$

Step 5: Calculate the pressure adjustment factor

\\Calculate the η factors for the system η_{syst} and the pressure adjustment factor γ_s.\\

$\eta_{syst} = (\log_{10}(\Pr(system)) + B) \,/\, A$

$\gamma_s = \gamma_m \,/\, \eta_{syst}$

Step 6: Calculate the pressure resistance of the pipeline including the system effect

\\Calculate the pressure resistance of the pipeline including system effect by iteration of step 2 to 5 where next iteration have updated "design pressure" given as the pressure adjustment factor, γ_s, times the previous "design pressure". When γ_s converges to 1 this corresponds to the pressure resistance of the pipeline including system effects, and is given as γ_s times the "design pressure" of the last iteration.\\

Do until γ_s converges to 1

Step 2 to 5, where $\gamma_{inc} \cdot P_d(\text{next}) = \gamma_s \cdot \gamma_{inc} \cdot P_d(\text{previous})$

End loop

$P_{b,syst} = \gamma_s \cdot \gamma_{inc} \cdot P_d(\text{previous})$

D.6 Corrosion development – level 4

D.6.1 General

This section presents specification of the deliveries from level 4, see Figure D-1.

D.6.2 Evaluation of inspection data

In order to estimate the corrosion rate between two or more inspections, detailed inspection data from the inspections are needed. RWT_{SO} data is established from *WT* and *SO* data for all data joints and thereof *RBP*s, see [D.3].

The data sets should be compared in order to identify possible shifts in the data, i.e. in the axial or circumferential direction. Identified shifts should be adjusted for.

Note that the corrosion rates are calculated purely based on inspection data. It is advisable that the corrosion and its mechanism are evaluated by a corrosion expert.

The RWT_{SO} data should be checked for wall thickness deviations or bias, i.e. un-corroded wall should be equal in consecutive inspections. If this is not fulfilled, it should be evaluated whether the *RPB*s should be adjusted according to this possible bias, see more details in [D.6.2.1].

D.6.2.1 Assessment of possible bias

To assess the possible bias between two different inspections, profiles of the remaining wall thickness should be established for an area of the pipeline where there have been no or very little corrosion. The un-corroded wall thickness should be estimated by the median over at least 10 sensors in an un-corroded area, in order to ignore errors and small corrosion pitting. For channelling corrosion located near the bottom of the pipe (i.e. at 6 o'clock), a reasonable area to check for a possible bias is on the vertical side of the cross section (i.e. at 3 or 9 o'clock). The bias between two inspections is estimated as the difference in un-corroded wall thickness between consecutive inspections (i.e. for every section of the CWT profiles based on the median of values across the sensors of the RWT_{SO} data in an un-corroded area). See algorithm in [D.6.2.2].

It should, however, be noted that the bias in an un-corroded area not necessarily is the same as in the corroded area (due to quality of cleaning in corroded vs. un-corroded area, different distances the sound wave has to travel in the different materials etc.). This should be assessed and taken into account.

Depending on which of the consecutive inspections that gives the highest un-corroded wall thickness, it can be either conservative or un-conservative to calculate the corrosion rate without accounting for the bias.

D.6.2.2 Algorithm for calculation of bias

Input: One array of remaining wall thickness, $RWT_{SO}()$, from an un-corroded area

Step 1: Find *Median*(*i*) value based on the $RWT_{SO}(i, j_{3/9}\text{-}5: j_{3/9}+5)$ values

For each row i in the $RWT_{SO}()$

\\Calculate the *Median* value for the corresponding position along the pipeline for 10 sensors around the 3 or 9 o'clock sensor ($j_{3/9}$)\\

$$Median(i) = \mathrm{Median}(RWT_{SO}(i, j_{3/9}\text{-}5: j_{3/9}+5))$$

Next i

Output: An array, *Median*(), with the median values and the corresponding relative length/position along the pipeline joint.

D.6.3 Calculation of corrosion rate

CWT (characteristic wall thickness) profiles are established from the *RBP*s by averaging over a section length of $k \cdot \sqrt{D \cdot t}$ where k = 20, see illustration in Figure D-5. Corrosion rates are calculated for every section of the *CWT* profiles as the difference in wall thickness between the two inspections. The rate is divided by the number of years between the inspections to give a yearly corrosion rate.

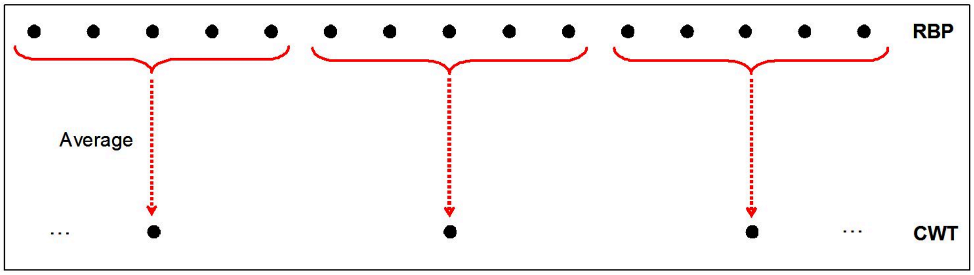

Figure D-10 Illustration of calculation of characteristic wall thickness profile (CWT)

D.6.3.1 Variations in rate along the pipeline

The corrosion rate could be varying along the pipeline length. The calculated corrosion rates for every section should be plotted versus location (KP) in order to identify this (e.g. as in Figure D-6). From the plot significant variations in the rate along the pipeline can be identified. Based on this plot, it should be evaluated whether it is appropriate to estimate one rate to be representative for the entire pipeline, alternatively estimate rates for different areas of the pipeline.

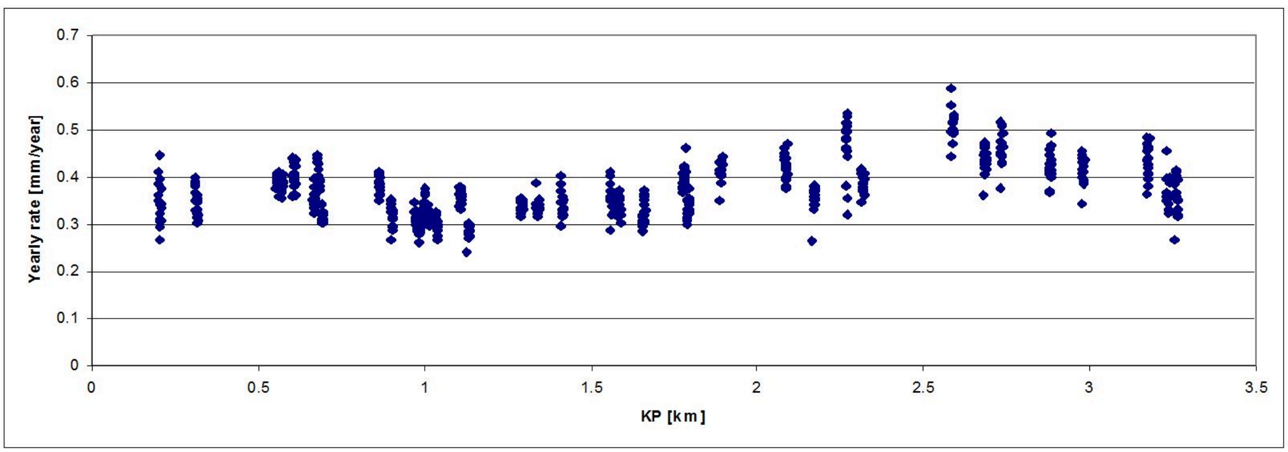

Figure D-11 Calculated corrosion rate along the pipeline

D.6.3.2 Representative corrosion rate

Based on the decision made in the previous sections, corrosion rate calculations are considered for the various areas of the pipelines and for the various initial corrosion depths. The following three corrosion rates could be calculated.

— the average corrosion rate

— the upper 95% quantile is calculated as $\mu + 1.645\sigma$, where μ and σ are the average and standard deviation respectively

— local rate.

The corrosion rate should not be under-estimated; hence considering only the average or local rate could give un-conservative conclusions. If considering the local rate, a suggestion is to increase the local rate by 20-30% in order to get a conservative estimate.

D.6.4 Pressure resistance versus time

Assuming uniform corrosion, the pressure resistance including system effect of the pipeline could be estimated as described in [D.5], based on *MAV* profiles with a general wall thickness reduction. The capacity calculation can be performed increasing the wall thickness reduction, e.g. from one to a few millimetres depending on nominal wall thickness and on how close the system capacity is to the design pressure.

Alternatively, the *MAV* profiles can be reduced according to the local rates calculated for every section of the *CWT* profiles (in [D.6.3]). Then the safe working pressure including system effect is calculated for *MAV* profiles reduced by the local rate for every section times the number of years forward considered.

To identify capacity development with time, the relation between capacity and number of years from the latest inspection can be illustrated based on the capacity calculations with reduced wall thickness, see example in Figure D-7. This shows the influence of the various calculated corrosion rates and estimates of the time to de-rating of design pressure is given by the relation between the pressure capacity and time with corrosion development. See algorithm in [D.6.4.1].

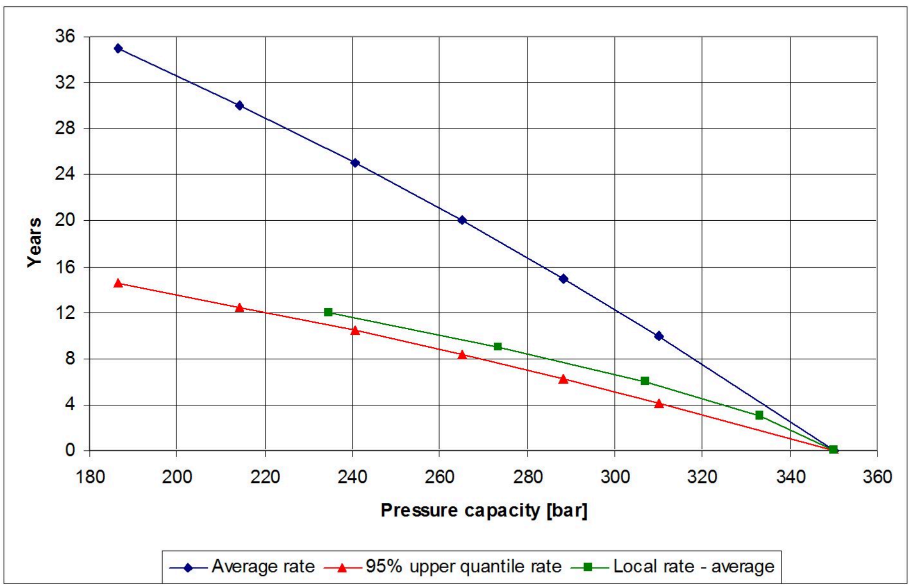

Figure D-12 Year versus pressure capacity with applied corrosion rate

D.6.4.1 Algorithm for safe working pressure versus time

Input: *MAV* profiles for all joints considered

Estimated corrosion rate

Step 1: Calculate capacity based on reduced *MAV* profiles

\\For wall thickness reduction of 1 to *m* mm, calculate the system capacity of the pipeline according to Sec.D.5.\\

For *i* = 1 to *m*

For each joint

\\Establish *MAV* profiles with general wall thickness reduction of *i* mm.\\

Next joint

\\Calculate system capacity of pipeline according to Sec.D.5.\\

Next *i*

Step 2: Calculate corresponding years for each wall thickness reduction based on corrosion rate.

\\For each wall thickness reduction of 1 to *m* mm, calculate the corresponding number of years with the established corrosion rate.\\

For *i* = 1 to *m*

\\Calculate the number of years as *i* divided by the corrosion rate.\\

Next *i*

Step 3: Plot number of years versus corresponding calculated system capacity

\\Plot number of years versus corresponding calculated system capacity.\\

Output: **Plot of number of years versus pipeline system capacity**

APPENDIX E DETAILED BURST CAPACITY EQUATION

E.1 Limit state formulation

The probability of failure due to burst is modelled as

$$P(G < 0)$$

where

$$G = P_{cap} - P_{oper}$$

P_{oper} is differential pressure and P_{cap} is the burst pressure capacity. The burst capacity equation presented below was used in the calibration of safety factors and in the derivation of the simplified capacity equation introduced in [2.1]. When failure is determined as loss of containment, the probability of failure is defined as the probability of bursting or leakage. The probability of having a leak can be calculated as $P(d_m/t > 1)$ where d_m is the measured defect depth and t is the pipe wall thickness.

E.2 Burst capacity equation

The burst capacity equation was established originally using the NG-18 and B31G equations, and is expressed as

$$P_{cap} = Y_{lab} Y_{FEA} P_{fit}$$

where

$$P_{fit} = P_0 R \text{ and } P_0 = Y_B \frac{2t \cdot UTS}{D - t}$$

Here P_0 is the plain (corrosion-free) pipe capacity, R is the reduction factor due to corrosion and the terms Y_{lab} and Y_{FEA} are model uncertainties given by comparing the predicted capacities to laboratory tests and FE analysis respectively. The term Y_B accounts for the boundary conditions of the pipe where

$$Y_B = \begin{cases} 1.00 \text{ for unconstrained pipe} \\ 1.08 \text{ for constrained pipe} \\ 1.10 \text{ for end-caped pipe} \end{cases}$$

The reduction factor, R, is given as

$$R = \frac{1 - \frac{d}{t}}{1 - \frac{d}{t}\frac{1}{f_1\left(L/\sqrt{Dt}\right)}} f_2\left(L/\sqrt{Dt}, t/D, d/t, \sigma_y/\sigma_u\right),$$

where the functions f_1 and f_2 are obtained through a multivariate curve fitting analysis, i.e. the expression for the burst capacity equation was calibrated from the outcome of the FE analyses.

The terms f_1, f_2 and Y_B together with the model uncertainties have undergone minor modifications since the capacity equation was first introduced. In order to remain consistent with respect to the safety factors and simplified equation presented in this Recommended Practice, the equation used in calibration of the safety factors is considered. This is obtained by choosing f_1, f_2 and Y_B as follows

$$Y_B = 1.08$$

$$f_1 = 1 + 0.002X^3,\ X = L/\sqrt{Dt}$$

$$f_2 = HQ$$

The terms H and Q in the expression for f_2 are given as

$$H = \begin{cases} 1 - H_1 H_2\ for\ X \leq c_3 \\ 1\ for\ X > c_3 \end{cases},\ X = L/\sqrt{Dt}$$

$$H_1\left(\frac{t}{D}, \frac{d}{t}\right) = b_1 + b_2\frac{t}{D} + b_3\frac{d}{D} + b_4\frac{t^2}{D^2}$$

$$H_2\left(X, \frac{d}{t}\right) = c_1 X^{c_2}\left(1 - \frac{X}{c_3}\right)^{c_4} \cdot \left(1 + \frac{X}{c_3}\right) \cdot \left(\frac{d}{t}\right)^{c_5}$$

and

$$Q = \begin{cases} 1 - Q_1 Q_2\ for\ X \leq e_3 \\ 1\ for\ X > e_3 \end{cases},\ X = L/\sqrt{Dt}$$

$$Q_1(B) = e_1 B^2 + e_2 B,\ B = \frac{1.3\sigma_y}{UTS} - 1$$

$$Q_2\left(X, \frac{d}{t}\right) = X^{e_4}\left(1 - \frac{X}{e_3}\right)^{e_5} \cdot \left(1 + \frac{X}{e_3}\right) \cdot \left(\frac{d}{t}\right)^{e_6}$$

where the constants b_i, c_i and e_i are given in Table E-1.

Table E-1

b1 = 1.6	c1 = 0.4	e1 = -0.5
b2 = -3	c2 = 1.15	e2 = -1
b3 = -2	c3 = 25.5	e3 = 16
b4 = 2	c4 = 8	e4 = 0.5
	c5 = 1.5	e5 = 5
		e6 = 1

CHANGES – HISTORIC

There are currently no historical changes for this document.

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