

RECOMMENDED PRACTICE
RP-F101

CORRODED PIPELINES

1999

FOREWORD

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The Recommended Practice publications (RP-series) cover proven technology and solutions which have been found by DNV to represent good practice, and which represent one alternative for satisfying the requirements stipulated in the DNV Offshore Standards or other codes and standards cited by DNV. The DNV RP-series is divided into 6 parts, as follows:

- A. Quality and Safety Methodology
- B. Materials Technology
- C. Structures
- D. Systems
- E. Special Facilities
- F. Pipelines & Risers

As well as forming the technical basis for DNV verification services, the Offshore Standards and Recommended Practices are offered as DNV's interpretation of safe engineering practice for general use by the offshore industry.

ACKNOWLEDGEMENTS

This Recommended Practice is based upon a project guideline developed in a co-operation between BG Technology and DNV. 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)
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- Saudi Arabian Oil Company
- Shell UK Exploration and Production, Shell Global Solutions, Shell International Oil Products B.V.
- Statoil
- Total Oil Marine plc

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

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Program description, code compliance program for DNV RP-F101 Corroded Pipelines

The program calculates the allowable operating pressure of pipelines containing corrosion defects.

Examples of calculation:

DNV Recommended Practice, RP-F101 Corroded Pipelines
Single defect, section 3, Part A

Developed by: Det Norske Veritas, Pipeline Section

PROJECT INFORMATION

Project title: Recommended practice
Project no.: Demo
Client: Example
Subject: Example

Safety class, material and inspection capabilities

Safety Class: Normal
Material req. "L": NO
Material Grade: X60
(SNTS: 413.2 N/mm²)
(SMTS: 517.1 N/mm²)

Inspection method: Relative (MFL)
Inspection capabilities: AO
Confidence level (%): 0
Sizing accuracy: 0 % of beam

Geometry, load, density and reference height

Outer diameter (D): 762.0 mm (30.00 inch) Ind. ANN: Dst 14.5
Wall thickness (t): 22.10 mm (0.87 inch)
P_{ref} (at ref. height): 150.0 bar (2176 psi)
Reference height: 40.0 m
Water density: 1023.0 kg/m³ (pipe height is above sea level)
Containment density: 210.0 kg/m³ Height, at defect: 5.0 m

Specification of defect size

Defect depth (d): 11.03 mm (50.0 % of t) STD(d): 0.0000
Defect length (l): 300.0 mm (2.11 (avg)(R))

Results

Allowable diff. pressure: 164.9 bar (2391 psi)
Allowable internal pressure at ref. height: 164.1 bar (2381 psi) Utilization: 0.91
Per additional defects, number of: 0

Single defect

DNV Recommended Practice, RP-F101 Corroded Pipelines
Complex defects, section 4, Part A

PROJECT INFORMATION

Project title: Recommended practice
Project no.: Demo
Client: Example
Subject: Example

Safety class, material and inspection capabilities

Safety Class: Normal
Material req. "L": NO
Material Grade: X60
(SMTS: 517.1 N/mm²)

Inspection method: Relative (MFL)
Inspection capabilities: AO
Confidence level (%): 80
Sizing accuracy: 0.0 % of beam

Outer diameter (D): 762.0 mm (30.00 inch) Reference height: 40.0 m
Wall thickness (t): 22.10 mm (0.87 inch) Containment density: 210.0 kg/m³
P_{ref} (at ref. height): 150.0 bar (2176 psi) Water density: 1023.0 kg/m³
Height, at defect: 5.0 m

Defect listing and results

Illustration of complex shape

Number of increments: 30
Allowable diff. pressure: 97.6 bar (1413 psi)
Allowable internal pressure at ref. height: 94.9 bar (1369 psi)

Point	Ident	Length (mm)	Depth (mm)
1	0	0	0
2	0	0	0
3	0	0.8	7.93
4	1	1.6	8.7
5	2	2.4	9.61
6	3	3.2	10.3
7	4	4	10.83
8	4.8	4.8	11.23
9	5.6	5.6	11.53
10	6.4	6.4	11.74
11	7.2	7.2	11.86
12	8	8	11.9
13	8.8	8.8	11.9
14	16.2	16.2	12.43
15	17.54	17.54	12.41
16	18.15	18.15	12.28
17	18.77	18.77	12.04
18	19.39	19.39	11.67
19	20	20	16.19
20	208.2	208.2	16.50

Complex shape

Program capabilities:

The program is based on the partial safety factor approach. The approach is described in part A of DNV RP-F101 Corroded Pipelines. The features of the program are described by the following code compliance capabilities:

- Single defect in pipe. Pipe subjected to internal pressure only
- Single defect in pipe. Pipe subjected to internal pressure, global bending and axial force
- Interacting defects
- Complex shaped defects

Program price:

The program price for maximum 5 users is:

10 000 NOK

For unlimited number of user, the program price is:

30 000 NOK

Contact address:

Det Norske Veritas AS

Pipeline Section, OCT 750,

Veritasveien 1

N - 1322 Høvik, Norway

Fax: (+47) 67 57 99 11

E-mail: pipeline@dnv.com

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1. General

1.1 Introduction

This document provides recommended practice for assessing pipelines containing corrosion. Recommendations are given for assessing corrosion defects subjected to:

- 1) Internal pressure loading only.
- 2) Internal pressure loading combined with longitudinal compressive stresses.

This Recommended Practice (RP) document describes two alternative approaches to the assessment of corrosion, 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 Part A, is in accordance to the safety philosophy adopted in the DNV Offshore Standard OS-F101, Submarine Pipeline Systems (/8/). This part of the RP is a supplement to, and complies with, DNV OS-F101. Uncertainties associated with the sizing of the defect depth and the material properties are specifically considered. Probabilistic calibrated equations (with partial safety factors) for the determination of the allowable operating pressure of a corroded pipeline are given.
- The second approach, given in Part B, is based on the ASD (Allowable Stress Design) 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

This document is a result of co-operation between BG Technology (part of BG plc) and DNV. The results from their respective joint industry projects have been merged, and form the technical basis for this recommended practice (/3/,/4/ and /16/).

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 the determination of partial safety factors.

1.3 Application

The methods provided in this document are intended to be used on corrosion defects in carbon steel pipelines (not applicable for other components) that have been designed to the DNV Offshore Standard OS-F101 Submarine Pipeline Systems, /8/,/9/ or other recognised pipeline design code as (but not limited to) ASME B31.4 /1/, ASME B31.8 /2/, BS8010 /5/, IGE/TD/1 /10/, ISO/DIS 13623 /11/, CSA Z662-94 /7/, provided that the safety philosophy is the design code is violated.

When assessing corrosion, the effect of continued corrosion growth should be considered. If a corroded region is to be left in service then measures should be taken to arrest further corrosion growth, or an appropriate inspection programme should be adopted. The implications of continuing defect growth are outside the scope of this document.

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

1.4 Structure of RP

The RP describes two alternative approaches. The first approach is given in Part A, which consists of section 2 through 5. The second approach is given in Part B, which consists of section 6 through 9.

A flow chart describing the assessment procedure (for both Part A and Part B) is shown in Figure 5.

Worked examples are given in Appendix A for the methods described in Part A. and Appendix B (for the methods described in Part B).

1.5 Applicable Defects

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

- 1) Internal corrosion in the base material.
- 2) External corrosion in the base material.
- 3) Corrosion in seam welds.
- 4) Corrosion in girth welds.
- 5) Colonies of interacting corrosion defects.
- 6) 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.

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1.6 Applied Loads

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

Internal pressure loading for:

- 1) Single defect
- 2) Interacting defects
- 3) Complex shaped defects

Internal pressure loading and combined with longitudinal compressive stresses for:

- 1) Single defects

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

Methods for assessing defects under combined internal pressure and tensile longitudinal stresses are given in Appendix D for the ASD approach (Part B).

The recommended practice given in this document is confined to the effects of internal pressure and compressive longitudinal loading on longitudinal failure because the validation of these effects was addressed in the DNV and 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 RP. Methods for assessing defects under combined internal pressure and bending loads, and/or tensile longitudinal loads, are recommended in other documents (e.g. /6/ and /12/). These methods have been included in Appendix D, in a format compatible with the rest of this document, for those who wish to use these methods.

1.7 Exclusions

The following are outside the scope of this document:

- 1) Materials other than carbon linepipe steel.
- 2) Linepipe grades in excess of X80¹.
- 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).

¹ The validation of the assessment methods comprised full scale tests on grades up to X65, and material tests on grades up to X80 (inclusive).

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, 9, 10.

³ Metal loss defects due to mechanical damage may contain a work hardened layer at their base and may also contain cracking.

The assessment procedure is only applicable to linepipe steels that are expected to fail through plastic collapse. The procedure is not recommended for applications where fracture is likely to occur. These may include:

- 10) Any material that has been shown to have a transition temperature above the operating temperature.
- 11) Material of thickness greater than 12.7 mm (1/2"), unless the transition temperature is below the operating temperature.
- 12) Defects in bond lines of flash welded (FW) pipe.
- 13) Lap welded or furnace butt welded pipe.
- 14) Semi-killed steels.

1.8 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, ref., (/6/, /12/, /14/).

1.9 Further Assessment

The intent of this RP is to provide simplified procedures for the assessment of corroded pipe. The results of the analysis should be conservative. If the corrosion defects are not found to be acceptable using the procedures given in this RP, then 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 and/or full scale testing.

1.10 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.

1.11 Validation

The methods given in this RP for assessing corrosion under internal pressure loading only 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 (26")
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
clt (circumferential)	0.01	to	22

(Shortest defect was l= 2.1 t)

For nomenclature, see section 1.13.

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 Sections 3.3 and 3.4, is not as comprehensive as the validation of the methods for the assessment of corrosion defects subject to internal pressure loading alone. The approach has not been validated for longitudinal corrosion defects with a circumferential length exceeding the longitudinal length. The partial safety factors have not been derived from an explicit probabilistic calibration.

1.12 Definitions

A *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.

An *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 it would be if the interacting defect was a single defect, because of the interaction with neighbouring defects.

A *Complex Shaped Defect* is a defect that results from combining colonies of interacting defects, or a single defect for which a profile is available.

1.13 Symbols and Abbreviations

A	=	Projected area of corrosion in the longitudinal plane through the wall thickness (mm^2).	F	=	Total usage factor.
A_c	=	Projected area of corrosion in the circumferential plane through the wall thickness (mm^2).		=	$F_1 F_2$
$A_{i,pit}$	=	Area of the 'i'th idealised 'pit' in a complex shaped defect (mm^2).	F_1	=	Modelling factor.
A_{patch}	=	Area of an idealised 'patch' in a complex shaped defect (mm^2).	F_2	=	Operational usage factor.
A_r	=	Circumferential area reduction factor.	F_x	=	External applied longitudinal force (N).
	=	$1 - A_c / \pi D t$	H_1	=	Factor to account for compressive longitudinal stresses.
	≈	$1 - (d/t)\theta$	H_2	=	Factor to account for tensile longitudinal stresses.
D	=	Nominal outside diameter (mm).	K, K_1 , K_2	=	Factor to determine σ_2 .
			M_Y	=	External applied bending moment (Nmm).
			N	=	Number of defects in a colony of interacting defects.
			N_m	=	Number of depth measurements taken to define the profile of a complex shaped defect.
			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_{f_j}	=	Failure pressure for 'j'th depth increment in a progressive depth analysis of a complex shaped defect (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).
			$P_{tensile}$	=	Failure pressure of the corroded pipe for a single defect subject to internal pressure and tensile longitudinal stresses (N/mm^2).
			P_{total}	=	Failure pressure of a complex shaped defect when treated as a single defect (N/mm^2).
			P_i	=	Failure pressures of an individual defect forming part of a colony of interacting defects (N/mm^2).
			RP	=	Recommended Practice
			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).
			SMTS	=	Specified minimum tensile strength (N/mm^2).
			SMYS	=	Specified minimum yield strength (N/mm^2).
			ULS	=	Ultimate Limit State
			UTS	=	Ultimate tensile strength (N/mm^2).
			YS	=	Yield strength (N/mm^2).
			YT	=	Yield to tensile ratio.
				=	YS/UTS or SMYS/SMTS
			Z	=	Circumferential angular spacing between projection lines (degrees).

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$E[X]$	=	Expected value of random variable X.	$P_{corr,comp}$	=	Allowable corroded pipe pressure of a single longitudinal corrosion defect under internal pressure and superimposed longitudinal compressive stresses (N/mm^2).
$Std[X]$	=	Standard deviation of random variable X.	p_i	=	Allowable corroded pipe pressures of individual defects forming a colony of interacting defects (N/mm^2).
$CoV[X]$	=	Coefficient of variation of random variable X.	P_{nm}	=	Allowable corroded pressure of combined adjacent defects n to m, formed from a colony of interacting defects (N/mm^2).
	=	$Std[X]/E[X]$	P_{patch}	=	Allowable corroded pipe pressure of an idealised 'patch' in a complex shaped defect (N/mm^2).
$(X)^*$	=	Characteristic value of X.	P_{total}	=	Allowable corroded pipe pressure of a complex shaped defect when treated as a single defect (N/mm^2).
c	=	Circumferential length of corroded region (mm).	r	=	Remaining ligament thickness (mm).
d	=	Depth of corroded region (mm).	s	=	Longitudinal spacing between adjacent defects (mm).
d_{ave}	=	Average depth of a complex shaped defect (mm).	s_i	=	Longitudinal spacing between adjacent defects forming part of a colony of interacting defects (mm).
	=	A/l_{total}	t	=	Uncorroded, measured, pipe wall thickness, or t_{nom} (mm).
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).	t_e	=	Equivalent pipe wall thickness used in a progressive depth analysis of a complex shaped defect (mm).
$d_{e,nm}$	=	Average 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).	ϵ_d	=	Factor for defining a fractile value for the corrosion depth.
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).	ϕ	=	Circumferential angular spacing between adjacent defects (degrees).
d_j	=	The 'j'th depth increment in a progressive depth analysis of a complex shaped defect (mm).	γ_d	=	Partial safety factor for corrosion depth.
d_{nm}	=	Average depth of a defect combined from adjacent defects n to m in a colony of interacting defects (mm).	γ_m	=	Partial safety factor for longitudinal corrosion model prediction.
d_{patch}	=	Average depth of an idealised 'patch' in a complex shaped defect (mm).	γ_{mc}	=	Partial safety factor for circumferential corrosion model prediction.
i	=	Isolated defect number in a colony of N interacting defects.	η	=	Partial safety factor for longitudinal stress for circumferential corrosion.
j	=	Increment number in a progressive depth analysis of a complex shaped defect.	θ	=	Ratio of circumferential length of corroded region to the nominal outside circumference of the pipe.
l	=	Longitudinal length of corroded region (mm).		=	$c/\pi D$
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).	σ_A	=	Longitudinal stress due to external applied axial force, based on the nominal wall thickness (N/mm^2).
l_j	=	Longitudinal length increment in a progressive depth analysis of a complex shaped defect (mm).	σ_B	=	Longitudinal stress due to external applied bending moment, based on the nominal wall thickness (N/mm^2).
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).	σ_L	=	Combined nominal longitudinal stress due to external applied loads (N/mm^2).
l_{total}	=	Total longitudinal length of a complex shaped defect (mm).	σ_1	=	Lower bound limit on external applied loads (N/mm^2).
P_{mao}	=	Maximum allowable operating pressure (N/mm^2).	σ_2	=	Upper bound limit on external applied loads (N/mm^2).
$P_{cap,patch}$	=	Capacity pressure of an idealised 'patch' in a complex shaped defect (N/mm^2).	ξ	=	Usage factor for longitudinal stress.
P_{corr}	=	Allowable corroded pipe pressure of a single longitudinal corrosion defect under internal pressure loading (N/mm^2).			
P_{corr_j}	=	Allowable corroded pressure for 'j'th depth increment in a progressive depth analysis of a complex shaped defect (N/mm^2).			
$P_{corr,circ}$	=	Allowable corroded pipe pressure of a single circumferential corrosion defect (N/mm^2).			

1.14 Units

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

2. Part A - Partial Safety Factor

2.1 Introduction

The approach given in Part A is based on the safety philosophy in the DNV Offshore Standard OS-F101, Submarine Pipeline Systems. Uncertainties associated with the sizing of the defect depth and the material properties are specifically considered. Probabilistic calibrated equations for the determination of the allowable operating pressure of a corroded pipeline are given. These equations are based on the LRFD (Load and Resistance Factor Design) methodology. It should be noted that the calibrated equations for allowable pressure are different from the capacity equation used in the calibration, /16/.

Partial safety factors are given for two general inspection methods (based on relative measurements e.g. magnetic flux leakage, and based on absolute measurements e.g. ultrasonic), four different levels of inspection accuracy, and three different reliability levels corresponding to the Safety Class classification in DNV OS-F101.

Guidance note

DNV OS-F101, Submarine Pipeline Systems, /8/ is the update of the DNV Rules for Submarine Pipeline Systems (DNV'96) /9/.

The safety philosophy and the Safety Class classification is the same in both the above mentioned documents.

The specification of the material requirements has been updated. Fulfilling the additional material requirements in DNV'96, sec. 5 C205 is in this context be regarded equivalent to the supplementary requirement "U" in DNV OS-F101, referred to in Table 2.3, Table 2.6, Table 2.7 and Table 2.8 in this document.

---e-n-d---o-f---Guidance note---

2.2 Reliability Levels

The partial safety factors and the corresponding fractile values are based on a code calibration and are defined for three reliability levels (corresponding to the Safety Class classification given in DNV OS-F101). The partial safety factors and the fractile values account for uncertainties in pressure, material properties, quality and tolerances in the pipe manufacturing process, sizing accuracy of the corrosion defect, etc..

Pipeline design is normally to be based on Location Class, Fluid Category and potential failure consequence for each failure mode, and to be classified into safety classes.

The following Safety Classes are considered (ref. DNV OS-F101 Section 2):

Safety Class	Indicating a target annual failure probability of:
High	$< 10^{-5}$
Normal	$< 10^{-4}$
Low	$< 10^{-3}$

Oil and gas pipelines, where no frequent human activity is anticipated, will normally be classified as Safety Class Normal. 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 pipelines. For more details see OS-F101, section 2.

2.3 Inspection Sizing Accuracy

The inspection sizing accuracy is commonly given relative to the wall thickness and for a specified confidence level. The confidence level indicates the portion of the measurements that will fall within the given sizing accuracy. Assuming a Normal distribution, the following standard deviations can be estimated:

Table 2.2 Standard Deviation and Confidence Level

Relative sizing accuracy	Confidence level	
	80%	90%
Exact	StD[d/t] = 0.00	StD[d/t] = 0.00
$\pm 5\%$ of t	StD[d/t] = 0.04	StD[d/t] = 0.03
$\pm 10\%$ of t	StD[d/t] = 0.08	StD[d/t] = 0.06
$\pm 20\%$ of t	StD[d/t] = 0.16	StD[d/t] = 0.12

The following figure illustrates a sizing accuracy of $\pm 5\%$ of t , quoted with a confidence level of 80%. A Normal distribution is assumed.

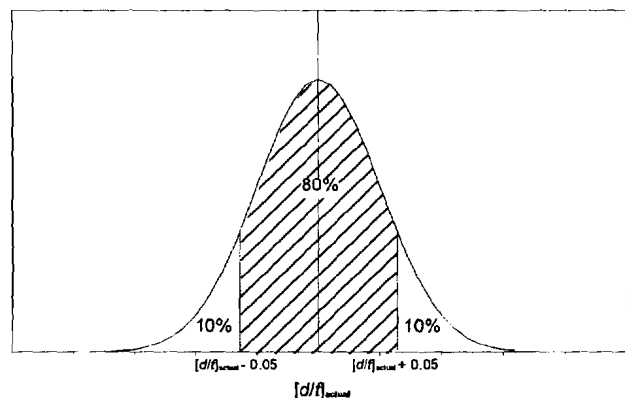


Figure 1 - Example of a Sizing Accuracy of $\pm 5\%$ of t , quoted with a Confidence Level of 80%.

2.4 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.

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The acceptance equation is based on the use of 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).

2.5 Material Grade and material requirements

The specified minimum tensile strength (SMTS) is used in the acceptance equation. This is given in the linepipe steel material specification (e.g. API/5L, /15/) for each material grade.

The values for the partial safety factors γ_m and γ_{mc} used in the acceptance equation depend upon the material supplementary requirements "U" as defined in DNV OS-F101, section 6.

The specified material requirement "U" shall be taken as not specified (NO) unless it can be documented that the requirements are fulfilled as defined in DNV OS-F101.

If the material properties are known in more detail (e.g. a number of individual mill certificates are available), then the SMTS to be used in the acceptance equation may be calculated according to the definition given below provided that CoV[σ_u] is less than 0.06:

$$SMTS = E[\sigma_u] / 1.09$$

Guidance note

In case of high operating temperature a reduction in the material tensile strength should be considered. The reduction is highly material dependent and should preferably be based on detailed knowledge of the actual material. In lack of any material information a linear reduction of 10% from 50°C up to 200°C should be used for linepipe material.

---e-n-d---o-f---Guidance note---

2.6 Relative Depth Measurement

Partial safety factors are given in Table 2.3 for inspection results based on relative depth measurements, (e.g. Magnetic Flux Leakage (MFL) intelligent pig measurements) where the defect depth measurement and the accuracy are given as a fraction of the wall thickness.

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.

The values for the partial safety factor γ_m in Table 2.3 is dependent on the material supplementary requirements "U" as defined in DNV OS-F101:

Supplementary requirements "U" specified	Safety Class		
	Low	Normal	High
NO	$\gamma_m = 0.79$	$\gamma_m = 0.74$	$\gamma_m = 0.70$
YES	$\gamma_m = 0.82$	$\gamma_m = 0.77$	$\gamma_m = 0.73$

Partial safety factors are given in Table 2.4 for various levels of inspection accuracy (defined in terms of the standard deviation) and Safety Class:

Inspection sizing accuracy, StD[d/t]	ϵ_d	Safety Class		
		Low	Normal	High
(exact) 0.00	0.0	$\gamma_d = 1.00$	$\gamma_d = 1.00$	$\gamma_d = 1.00$
0.04	0.0	$\gamma_d = 1.16$	$\gamma_d = 1.16$	$\gamma_d = 1.16$
0.08	1.0	$\gamma_d = 1.20$	$\gamma_d = 1.28$	$\gamma_d = 1.32$
0.16	2.0	$\gamma_d = 1.20$	$\gamma_d = 1.38$	$\gamma_d = 1.58$

The following polynomial equations can be used to determine the appropriate partial safety factors and fractile values for intermediate values of StD[d/t] given in Table 2.5. The polynomial equations are curve fits based on the calibrated factors given in Table 2.4. The curves are also shown in Figure 2 and Figure 3.

Safety Class	γ_d	Range
Low	$\gamma_d = 1.0 + 4.0 \text{StD}[d/t]$	StD[d/t] < 0.04
	$\gamma_d = 1 + 5.5 \text{StD}[d/t] - 37.5 \text{StD}[d/t]^2$	0.04 ≤ StD[d/t] < 0.08
	$\gamma_d = 1.2$	0.08 ≤ StD[d/t] ≤ 0.16
Normal	$\gamma_d = 1 + 4.6 \text{StD}[d/t] - 13.9 \text{StD}[d/t]^2$	StD[d/t] ≤ 0.16
High	$\gamma_d = 1 + 4.3 \text{StD}[d/t] - 4.1 \text{StD}[d/t]^2$	StD[d/t] ≤ 0.16

$$\epsilon_d = \left\{ \begin{array}{ll} 0 & \text{StD}[d/t] \leq 0.04 \\ -1.33 + 37.5 \text{StD}[d/t] - 104.2 \text{StD}[d/t]^2 & 0.04 < \text{StD}[d/t] \leq 0.16 \end{array} \right\}$$

The variation of the partial safety factors ϵ_d and γ_d with $StD[d/t]$ are shown in the following two figures:

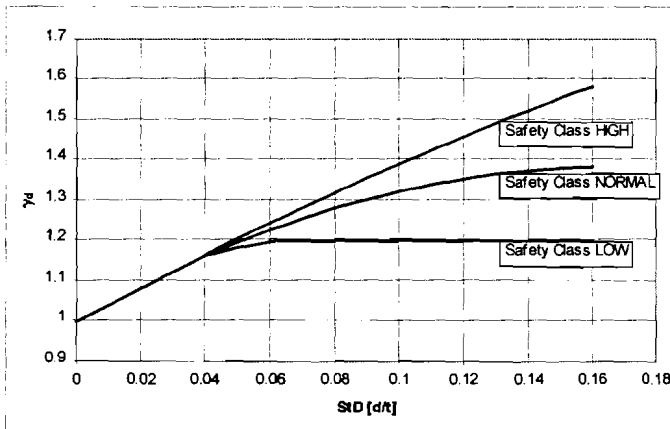


Figure 2 - Partial Safety Factor γ_d with $StD[d/t]$.

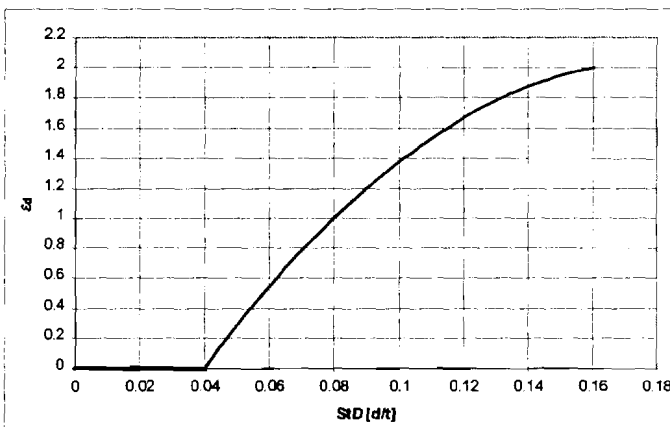


Figure 3 - Safety Factor ϵ_d with $StD[d/t]$.

2.7 Absolute Depth Measurement

Partial safety factors are given in Table 2.6 for inspection results based on absolute depth measurements (e.g. Ultrasonic Wall Thickness or Wall Loss Measurements), where the local wall thickness, the defect depth measurement and the accuracy are given directly. The measured values of the wall thickness (t) should be used in the calculation of the allowable pressure.

The values for the partial safety factor γ_m in Table 2.6 is dependent on the material supplementary requirements "U" as defined in DNV OS-F101.

Table 2.6 Partial Safety Factors γ_m , Absolute Depth Measurement			
Supplementary requirements "U" specified	Safety Class		
	Low	Normal	High
NO	$\gamma_m = 0.82$	$\gamma_m = 0.77$	$\gamma_m = 0.72$
YES	$\gamma_m = 0.85$	$\gamma_m = 0.80$	$\gamma_m = 0.75$

The partial safety factor γ_d and the fractile value ϵ_d to be used with absolute depth measurements are the same as those for relative depth measurements, and are given in Table 2.4 and Table 2.5. The partial safety factor γ_m is different because it, for absolute measurements, is assumed that the pipe wall thickness around the corroded area is measured with at least the same accuracy as the corrosion depth.

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

2.7.1 If the remaining ligament thickness (r) and the wall thickness (t) are measured:

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

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

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

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:

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

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

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

The partial safety factors are given in Table 2.5 (for γ_d and ϵ_d) and Table 2.6 (for γ_m).

2.7.2 If the corrosion depth (d) and the wall thickness (t) are measured:

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

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

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

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).

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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:

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

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

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

The partial safety factors are given in Table 2.5 (for γ_d and ϵ_d) and Table 2.6 (for γ_m).

2.8 Circumferential Corrosion

Partial safety factors are given in Table 2.7 and Table 2.8 for a single circumferential corrosion defect under internal pressure and longitudinal compressive stresses.

The values for the partial safety factor γ_{mc} in Table 2.7, and η in Table 2.8 is dependent on the material supplementary requirements "U" as defined in DNV OS-F101:

Table 2.7 Partial Safety Factors γ_{mc}			
Supplementary requirements "U" specified	Safety Class		
	Low	Normal	High
NO	$\gamma_{mc} = 0.81$	$\gamma_{mc} = 0.76$	$\gamma_{mc} = 0.71$
YES	$\gamma_{mc} = 0.85$	$\gamma_{mc} = 0.80$	$\gamma_{mc} = 0.75$

Table 2.8 Partial Safety Factors η			
Supplementary requirements "U" specified	Safety Class		
	Low	Normal	High
NO	$\eta = 0.96$	$\eta = 0.87$	$\eta = 0.77$
YES	$\eta = 1.00$	$\eta = 0.90$	$\eta = 0.80$

Guidance note

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.

---e-n-d---o-f---Guidance note---

2.10 System Effect

The target reliability levels are for a single metal loss defect. If the defect in question is clearly the most severe defect, in terms of the allowable corroded pipe pressure, then this defect will govern the reliability level of the pipeline for failure due to corrosion. In the case of several corrosion defects with approximately the same allowable corroded pipe pressure, or a pipeline with a large number of corrosion defects, the system effect must be accounted for when determining the reliability level of the pipeline. Adding the failure probability of each defect will conservatively assess the system effect.

2.9 Usage Factors for Longitudinal Stress

The usage factors for longitudinal stress are given in Table 2.9.

Table 2.9 Usage Factors ξ	
Safety Class	Usage Factor ξ
Low	$\xi = 0.90$
Normal	$\xi = 0.85$
High	$\xi = 0.80$

3. Assessment of a Single Defect (Part A)

3.1 Requirements

For a corrosion defect to be assessed as a single defect (see Figure 6), the defect must be an isolated defect.

Adjacent defects can interact to produce a failure pressure that is lower than the failure pressure of either of the isolated defects (if they were treated as single defects). For the case where interaction occurs, the single defect equation is no longer valid and the procedure given in Section 4 must be applied. Figure 8 shows the key dimensions for defect interaction.

A defect can be treated as an isolated defect if any of the following conditions are satisfied:

- 1)
- 2) The circumferential angular spacing between adjacent defects, ϕ

$$\phi > 360 \sqrt{\frac{t}{D}} \quad (\text{degrees})$$
- 3) The axial spacing between adjacent defects, s :

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

3.2 Longitudinal Corrosion Defect, Internal Pressure Loading Only

The allowable corroded pipe pressure of a single defect subject to internal pressure loading only is given by the following acceptance equation. The acceptance equation has not been validated for longitudinal corrosion defects with a circumferential length exceeding the longitudinal length.

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

where:

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

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

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

p_{corr} is not allowed to exceed p_{mao} .

Measured defects depths exceeding 85% is not accepted.

3.3 Longitudinal Corrosion Defect, Internal Pressure and Superimposed Longitudinal Compressive Stresses

This method is only valid for single defects.

The allowable corroded pipe pressure 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 allowable corroded pipe pressure, including the correction for the influence of compressive longitudinal stress:

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

where:

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

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

$p_{corr,comp}$ is not allowed to exceed p_{corr} .

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3.4 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 allowable corroded pipe pressure of a single circumferential 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 allowable corroded pipe pressure, including the correction for the influence of compressive longitudinal stress:

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

where:

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

$p_{corr,circ}$ is not allowed to exceed p_{mao} .

The longitudinal pipe wall stress in the remaining ligament is not to exceed $\eta \text{ SMYS}$, in tension or in compression. The longitudinal pipe wall stress shall include the effect of all loads, including the pressure.

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

where: σ_{L-nom} is the longitudinal stress in the nominal pipe wall.

4. Assessment of interacting defects (Part A)

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 minimum information required comprises:

- 1) The angular position of each defect around circumference of the pipe.
- 2) The axial spacing between adjacent defects.
- 3) Whether the defects are internal or external.
- 4) The length of each individual defect.
- 5) The depth of each individual defect
- 6) The width of each individual defect.

4.2 Allowable Corroded Pipe Pressure 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 allowable corroded pipe pressure 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 failure pressure.

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---Guidance note---

- 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 9).
- 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 $\pm Z$, they should be projected onto the current projection line (see Figure 10).

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 11). 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 12).

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

$$p_i = \gamma_m \frac{2 t SMTS (1 - \gamma_d (d_i / t)^*)}{(D - t) \left(\frac{1 - \gamma_d (d_i / t)^*}{Q_i} \right)} \quad i = 1 \dots N$$

where:

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

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

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

Guidance note:

STEPS 7 to 9 estimate the allowable corroded pipe pressure of all combinations of adjacent defects. The allowable corroded pipe pressure 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---Guidance note---

STEP 7 Calculate the combined length of all combinations of adjacent defects (see Figure 13 and Figure 14).

For defects n to m the total length is given by:

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

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 13):

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

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STEP 9 Calculate the allowable corroded pipe pressure of the combined defect from n to m (p_{nm}) (see Figure 14), using l_{nm} and d_{nm} in the single defect equation:

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

where:

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

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

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

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

Fully correlated depth measurements:

$$\text{StD}[d_{nm}/t] = \text{StD}[d/t]$$

Uncorrelated depth measurements:

$$\text{StD}[d_{nm}/t] = \frac{\sqrt{\sum_{i=n}^m l_i^2}}{l_{nm}} \text{StD}[d/t]$$

Guidance note

The differences between correlated and uncorrelated measurements are discussed in Appendix C. Assuming uncorrelated depth measurements will, in general, result in a significantly higher allowable corroded pipe pressure (because $\text{StD}[d_{nm}/t]$ is less than $\text{StD}[d/t]$). In cases where the conditions are not known it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---Guidance note---

STEP 10 The allowable corroded pipe 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.

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

p_{corr} is not allowed to exceed p_{mao} .

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

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

5. Assessment of Complex Shaped Defects (Part A)

5.1 Requirements

This method must 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 must be 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 must include all material between the start and end of the complex shaped defect.

5.2 Allowable Corroded Pipe Pressure 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 allowable corroded pipe pressure 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 15 and Figure 16. The allowable corroded pipe pressure of the 'pits' within the 'patch' is estimated by considering an equivalent pipe of reduced wall thickness. The capacity (failure pressure) 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 Section 4).

The estimated allowable corroded pipe pressure at a given depth increment, is the minimum of the allowable corroded pipe pressure of the 'patch', the idealised 'pits', and the allowable corroded pipe 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 allowable corroded pipe pressure. This is the allowable corroded pipe pressure of the complex shaped defect.

---e-n-d---o-f---Guidance note---

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 allowable corroded pipe pressure of the total profile (p_{total}), using d_{ave} and l_{total} in the single defect equation:

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

where:

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

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

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

Fully correlated depth measurements:

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

Uncorrelated depth measurements:

$$StD[d_{ave}/t] = \frac{1}{\sqrt{N_m}} StD[d/t]$$

Guidance note:

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

The differences between correlated and uncorrelated measurements are discussed in Appendix C. Assuming uncorrelated depth measurements will, in general, result in a significantly higher allowable corroded pipe pressure (because $StD[d_{ave}/t]$ is less than $StD[d/t]$). In cases where the conditions are not known it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---Guidance note---

STEP 3 Divide the maximum defect depth into increments, and perform the below calculations for all depth increments (d_j) (see Figure 15). 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 16). The recommended number of increments is between 10 and 50.

STEP 4 Calculate the average depth of an idealised 'patch' as follows (see Figure 16):

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

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

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

Calculate also for use in step 7:

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

where:

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

$$(d_{patch}/t)^* = (d_{patch}/t)_{meas} + \epsilon_d \text{StD}[d_{patch}/t]$$

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

Fully correlated depth measurements:

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

Uncorrelated depth measurements:

$$\text{StD}[d_{patch}/t] = \frac{1}{\sqrt{N_m}} \text{StD}[d/t]$$

Guidance note:

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

The differences between correlated and uncorrelated measurements are discussed in Appendix C. Assuming uncorrelated depth measurements will, in general, result in a significantly higher allowable corroded pipe pressure (because $\text{StD}[d_{patch}/t]$ is less than $\text{StD}[d/t]$). In cases where the conditions are not known it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---Guidance note---

STEP 6 For each of the idealised 'pits', calculate the area loss in the nominal thickness cylinder, as shown in Figure 16, for the current depth interval, and estimate the average depth of each of the idealised 'pits' from:

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

STEP 7 Estimate the effective thickness of an 'equivalent' pipe with the same failure pressure as the 'patch', ($p_{cap,patch}$), as calculated in STEP 5 (see Figure 15).

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

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

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

STEP 9 Calculate the corroded pipe pressure of all individual idealised 'pits' (p_1, p_2, \dots, 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:

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

where:

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

$$(d_{ei}/t_e)^* = (d_{ei}/t_e)_{meas} + \epsilon_d \text{StD}[d/t]$$

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

Guidance note:

STEPS 10 to 12 estimate the allowable corroded pipe pressures of all combinations of adjacent defects. The allowable corroded pipe pressure 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} .

---c-n-d---o-f---Guidance note---

STEP 10 Calculate the combined length of all combinations of adjacent defects (see Figure 13 and Figure 14). For defects n to m the total length is given by:

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

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 13):

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

STEP 12 Calculate the allowable corroded pipe pressure of the combined defect from n to m (p_{nm}) (see Figure 14), using l_{nm} , t_e and $d_{e,nm}$ in the single defect equation:

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

where:

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

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

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

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

Fully correlated depth measurements:

$$\text{StD}[d_{e,nm} / t_e] = \text{StD}[d / t]$$

Uncorrelated depth measurements:

$$\text{StD}[d_{e,nm} / t_e] = \frac{\sqrt{\sum_{i=n}^m l_i^2}}{l_{nm}} \text{StD}[d / t]$$

Guidance note:

The differences between correlated and uncorrelated measurements are discussed in Appendix C. Assuming uncorrelated depth measurements will, in general, result in a significantly higher allowable corroded pipe pressure (because $\text{StD}[d_{e,nm} / t_e]$ is less than $\text{StD}[d / t]$). In cases where the conditions are not known it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---Guidance note---

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

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

STEP 14 Repeat the STEP's 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 allowable pipe pressure according to the single defect equation in Section 3.2 using the maximum defect depth and the total length of the defect.

STEP 16 The allowable corroded pipe pressure 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 allowable pressure for a single defect calculated in STEP 15.

p_{corr} is not allowed to exceed p_{mao} .

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6. Part B - Allowable Stress Approach

6.1 Introduction

The approach given in Part B is based on the ASD (Allowable Stress Design) format. The failure pressure (capacity) 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.

In the equations that follow, the ultimate tensile strength (*UTS*) is quoted. If the ultimate tensile strength is not known then the specified minimum ultimate tensile strength should be used (i.e. substitute *SMTS* for *UTS*). The measured *UTS* can be obtained from the results of standard tensile tests on representative pipe specimens, or from mill certificates.

Guidance note

In case of high operating temperature a reduction in the material tensile strength should be considered. The reduction is highly material dependent and should preferably be based on detailed knowledge of the actual material. In lack of any material information a linear reduction of 10% from 50°C up to 200°C should be used for linepipe material.

---e-n-d---o-f---Guidance note---

6.2 Total Usage Factor

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

$$F_1 = 0.9 \text{ (Modelling Factor)}$$

$$F_2 = \text{Operational Usage Factor which is introduced to ensure a safe margin between the operating pressure and the failure pressure of the corrosion defect (and is normally taken as equal to the Design Factor)}$$

The **Total Usage Factor (*F*)** to be applied to determine the safe working pressure should be calculated from:

$$F = F_1 F_2$$

7. Assessment of a Single Defect (Part B)

7.1 Requirements

For a corrosion defect to be assessed as a single defect (see Figure 6), the defect must be an isolated defect. Adjacent defects can interact to produce a failure pressure that is lower than the failure pressure of either of the isolated defects (if they were treated as single defects). For the case where interaction occurs, the single defect equation is no longer valid and the procedure given in Section 8 must be applied. Figure 8 shows the key dimensions for defect interaction.

A defect can be treated as an isolated defect if any of the following conditions are satisfied:

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

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

- 2) The axial spacing between adjacent defects, s :

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

7.2 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):

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

where:

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

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

$$P_{sw} = F P_f$$

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.

7.3 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.

A method for assessing a single defect subject to tensile longitudinal and/or bending stresses is given in Appendix D.

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 7).

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

$$\sigma_L > \sigma_1$$

where:

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

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:

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

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):

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

where:

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

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

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

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

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

$$P_{sw} = F P_f$$

8. Assessment of Interacting Defects (Part B)

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 methods given in Section 7 for assessing corrosion defects under combined loads are only valid for single defects.

The minimum information required comprises:

- 1) The angular position of each defect around circumference of the pipe.
- 2) The axial spacing between adjacent defects.
- 3) Whether the defects are internal or external.
- 4) The length of each individual defect.
- 5) The depth of each individual defect
- 6) The width of each individual defect.

8.2 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---Guidance note---

- 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 9 - Corrosion Depth Adjustment for Defects with Background Corrosion.).
- 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 $\pm Z$, they should be projected onto the current projection line (see Figure 10).

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 11). 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 12 - Projection of Overlapping Internal and External Defects onto a Single Projection Line and the Formation of a Composite Defect.).

STEP 6 Calculate the failure pressures ($P_1, P_2 \dots P_N$) of each defect, to the N^{th} defect, treating each defect, or composite defect, as a single defect:

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

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 $n = 1 \dots N$ and $m = n \dots N$) is denoted P_{nm} .

---e-n-d---o-f---Guidance note---

STEP 7 Calculate the combined length of all combinations of adjacent defects (see Figure 13 and Figure 14). For defects n to m the total length is given by:

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

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 13):

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

STEP 9 Calculate the failure pressure of the combined defect from n to m (P_{nm}) (see Figure 14), using l_{nm} and d_{nm} in the single defect equation:

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

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.

$$P_f = \text{MIN}(P_1, P_2, \dots, P_N, P_{nm})$$

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

$$P_{sw} = F P_f$$

- 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.

9. Assessment of a Complex Shaped Defect (Part B)

9.1 Requirements

This method must 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 must be 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 must include all material between the start and end of the complex shaped defect.

9.2 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 15 and Figure 16. 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 Section 8).

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---Guidance note---

- 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:

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

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_i) (see Figure 15). 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_i), and into 'pits' which are deeper than the subdivision (see Figure 16). The recommended number of increments is between 10 and 50.

- STEP 4 Calculate the average depth of an idealised 'patch' as follows (see Figure 16):

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

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

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

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 16, for the current depth interval, and estimate the average depth of each of the idealised 'pits' from:

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

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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 15).

$$t_e = \frac{P_{patch} \cdot D}{(2 UTS + P_{patch})}$$

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

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

STEP 9 Calculate the failure pressure of all individual idealised 'pits' (P_1, P_2, \dots, 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:

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

where:

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

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 $n = 1 \dots N$ and $m = n \dots N$) is denoted P_{nm} .

---e-n-d---o-f---Guidance note---

STEP 10 Calculate the combined length of all combinations of adjacent defects (see Figure 13 and Figure 14). For defects n to m the total length is given by:

$$l_{nm} = l_m + \sum_{i=n}^{i=m-1} (l_i + s_i)_{n,m} = l \dots N$$

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 13):

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

STEP 12 Calculate the failure pressure of the combined defect from n to m (P_{nm}) (see Figure 14), using l_{nm} , t_e and $d_{e,nm}$ in the single defect equation:

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

where:

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

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

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

STEP 14 Repeat the STEP's 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 Section 7.2, 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:

$$P_{sw} = F P_f$$

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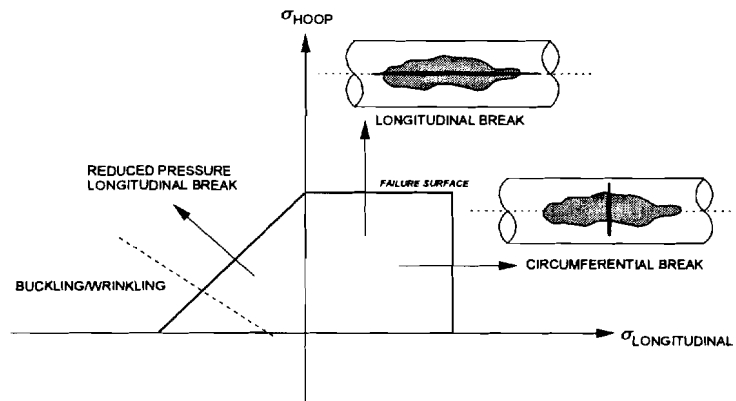


Figure 4 - Influence of Applied Loads on the Failure Mode of a Corrosion Defect.

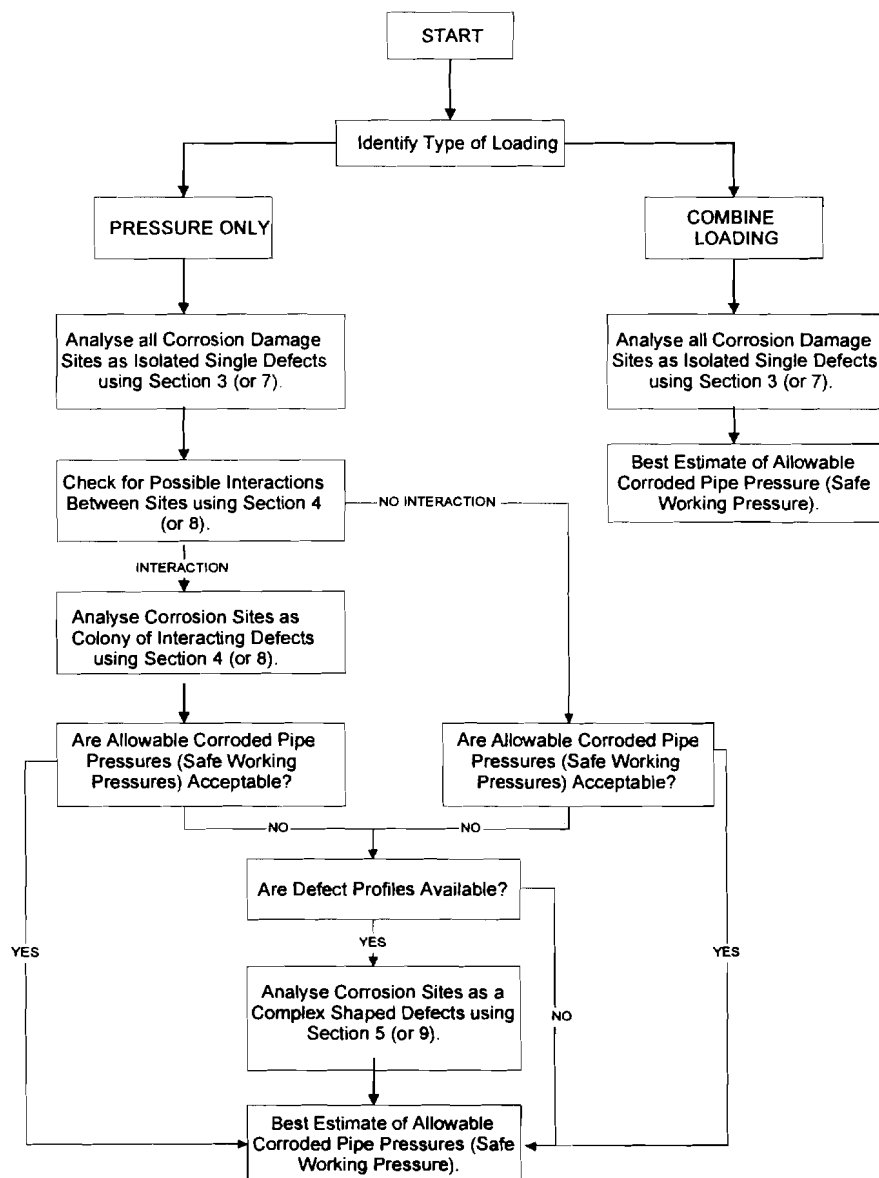


Figure 5 - Flow Chart of the Assessment Procedure.

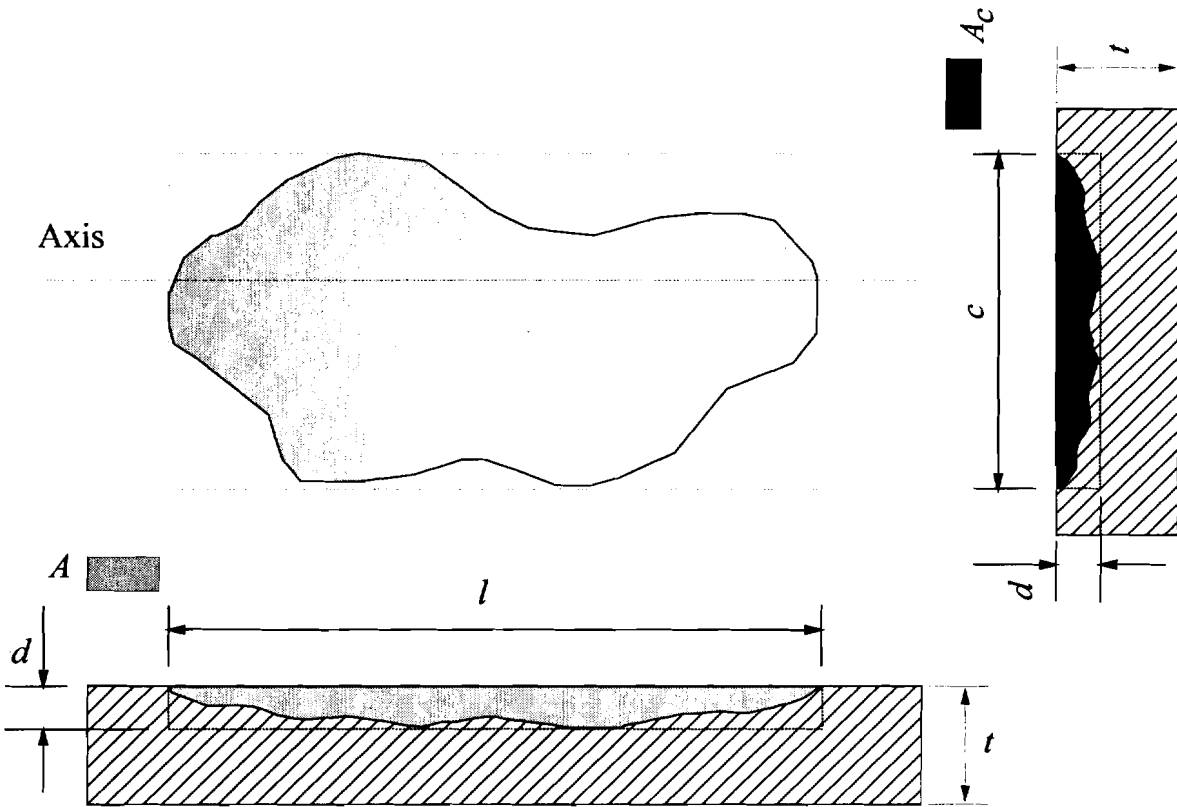


Figure 6 - Single Defect Dimensions.

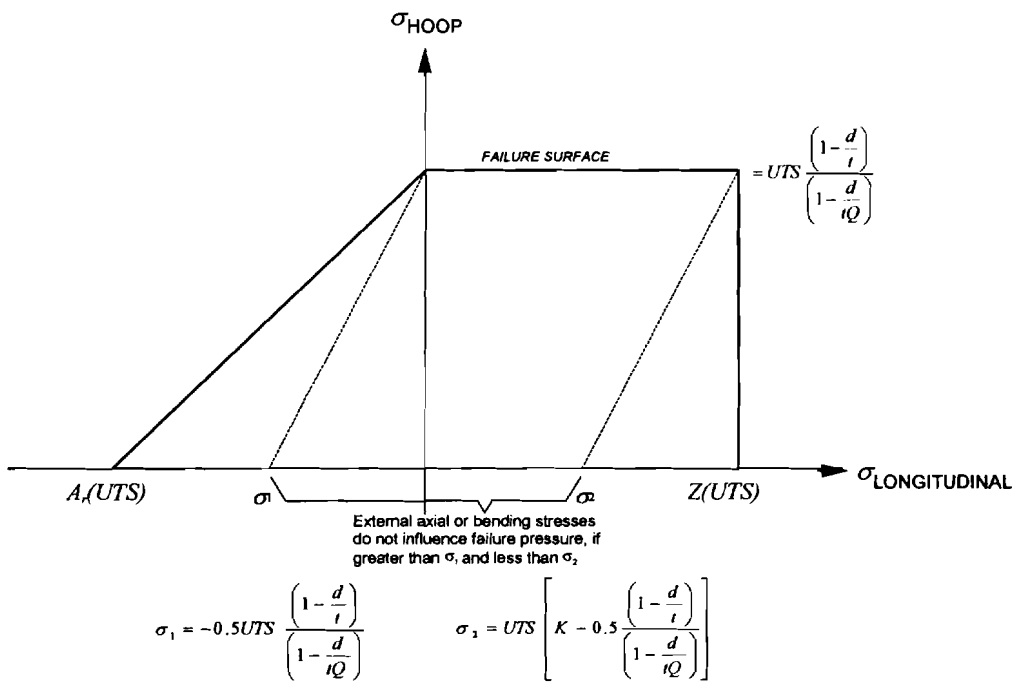


Figure 7 - Range of Superimposed Longitudinal and/or Bending Loads that will not Influence the Failure Pressure.

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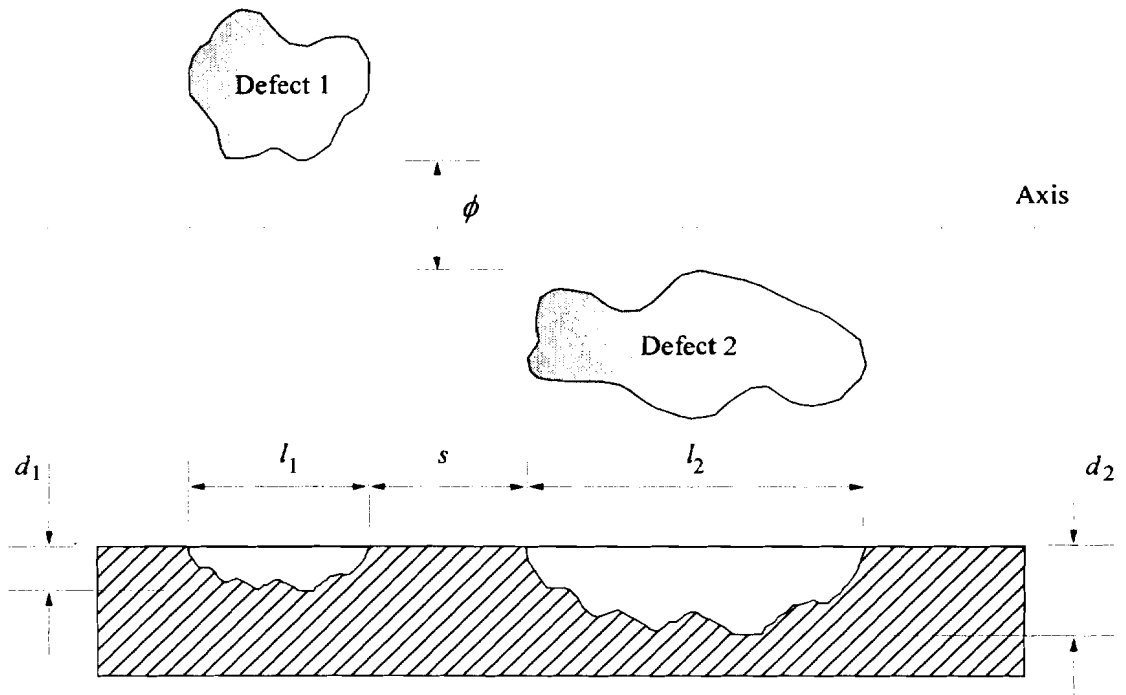


Figure 8 - Interacting Defect Dimensions.

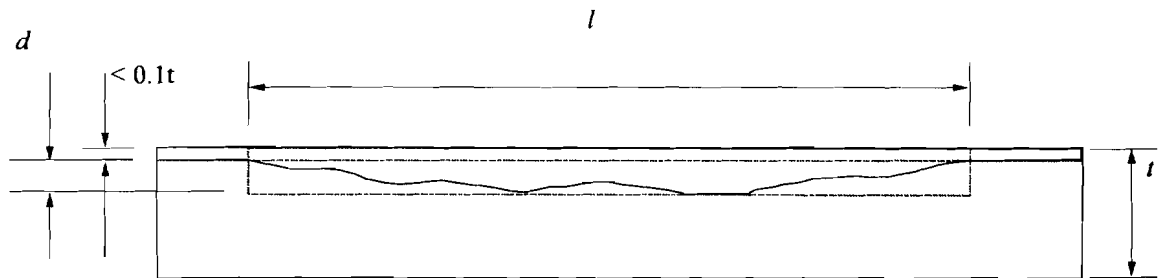


Figure 9 - Corrosion Depth Adjustment for Defects with Background Corrosion.

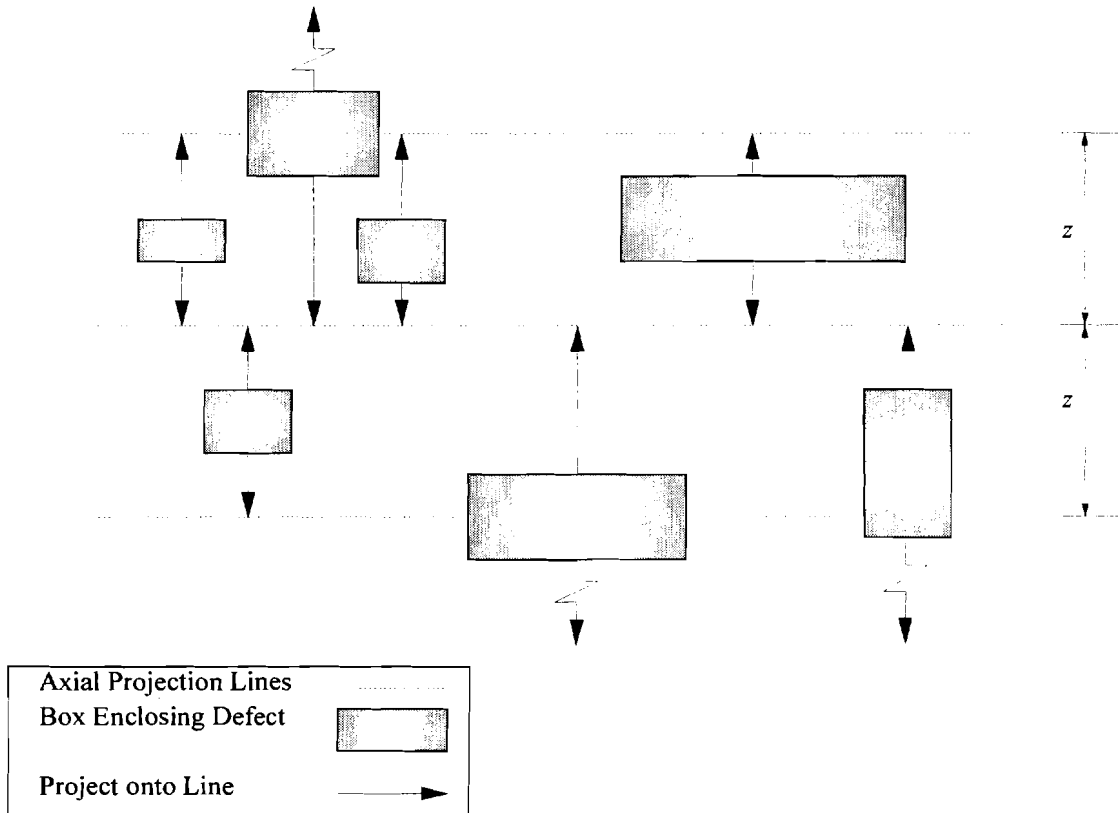


Figure 10 - Projection of Circumferentially Interacting Defects.

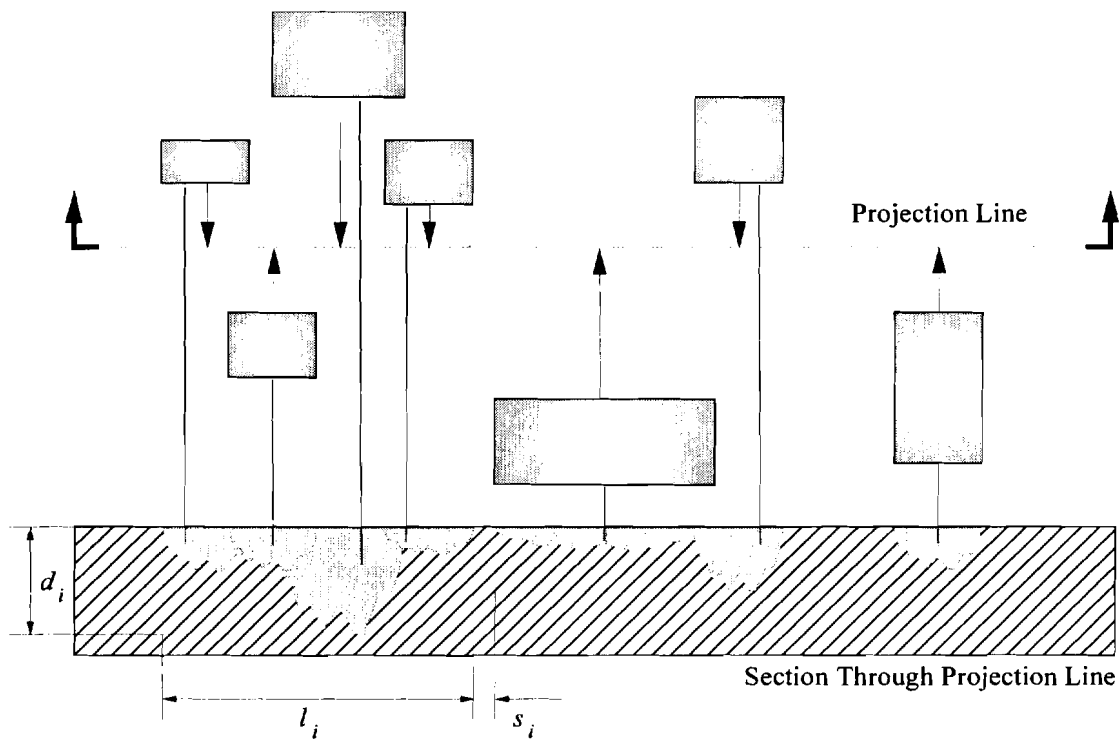


Figure 11 - Projection of Overlapping Sites onto a Single Projection Line and the Formation of a Composite Defect.

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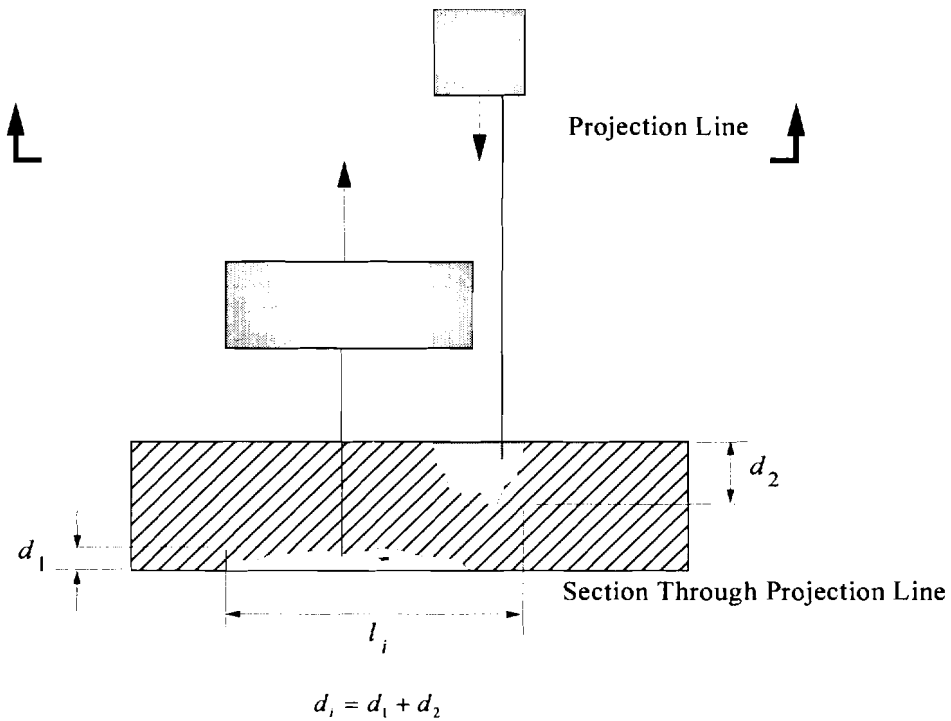
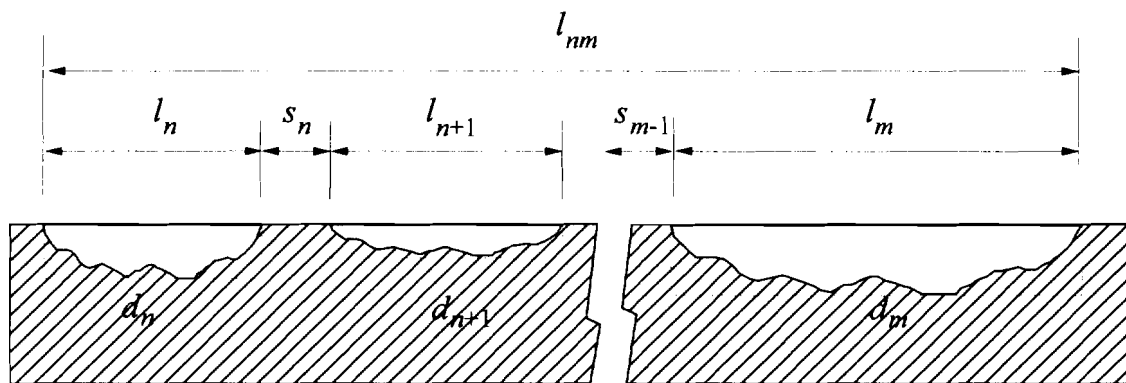


Figure 12 - Projection of Overlapping Internal and External Defects onto a Single Projection Line and the Formation of a Composite Defect.



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

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

Figure 13 - Combining Interacting Defects.

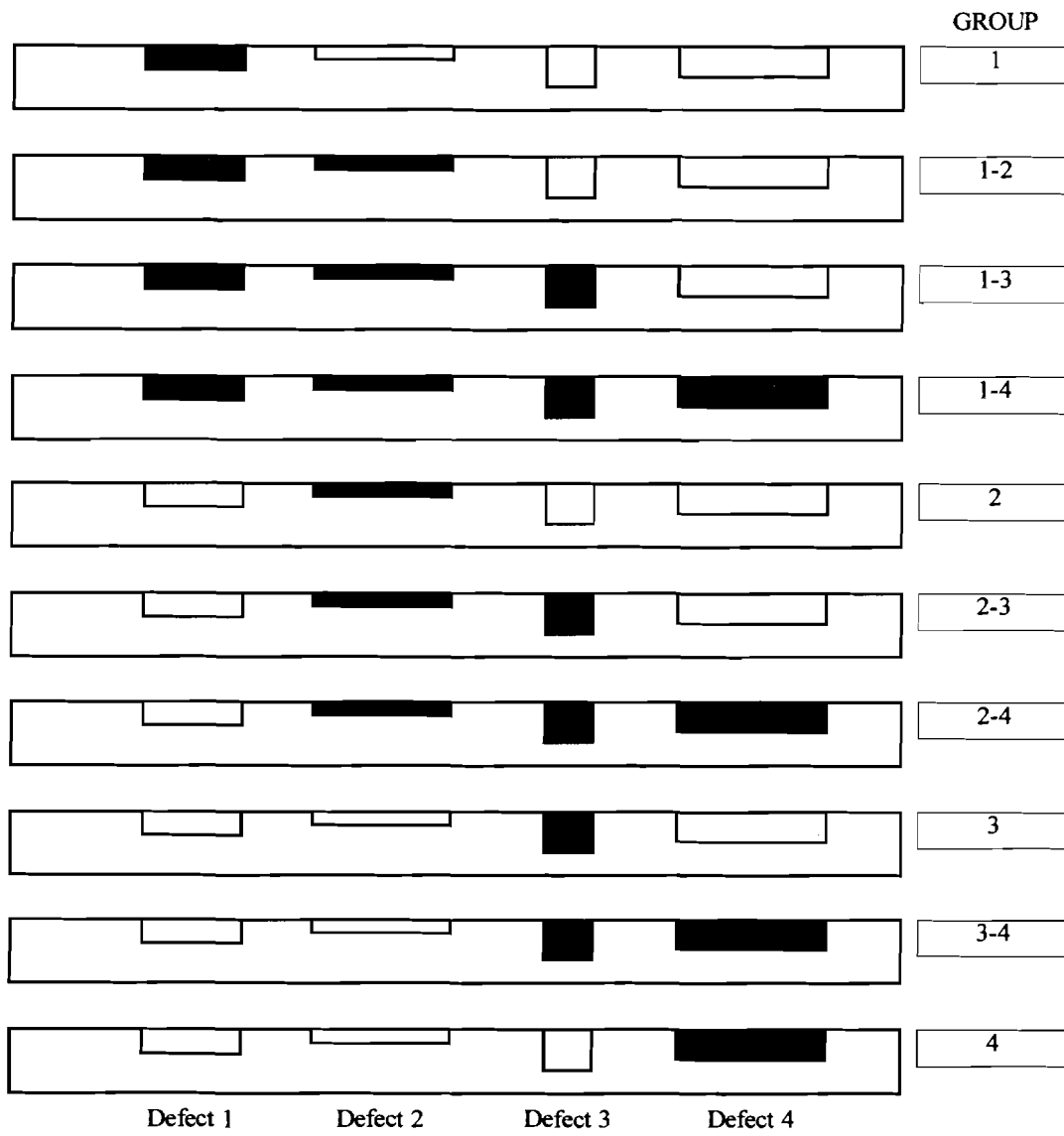


Figure 14 - Example of the Grouping of Adjacent Defects for Interaction to find the Grouping that gives the Lowest Estimated Failure Pressure.

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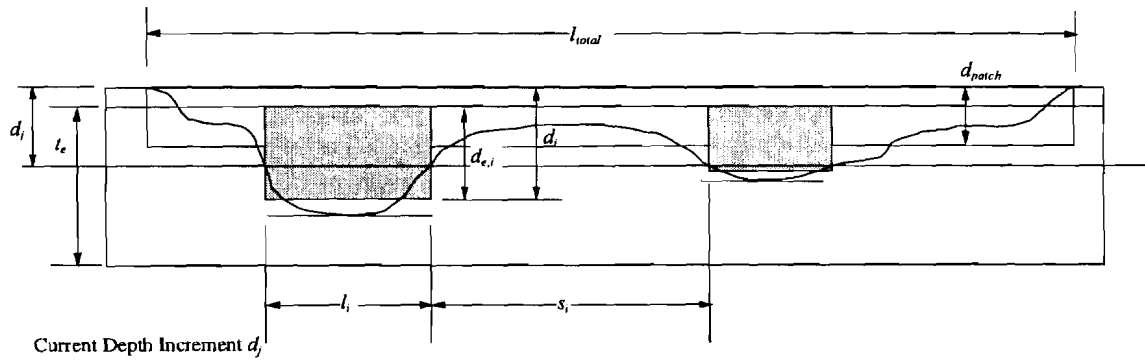


Figure 15 - Subdivision of Complex Shape into Idealised 'patch' and 'pits'.

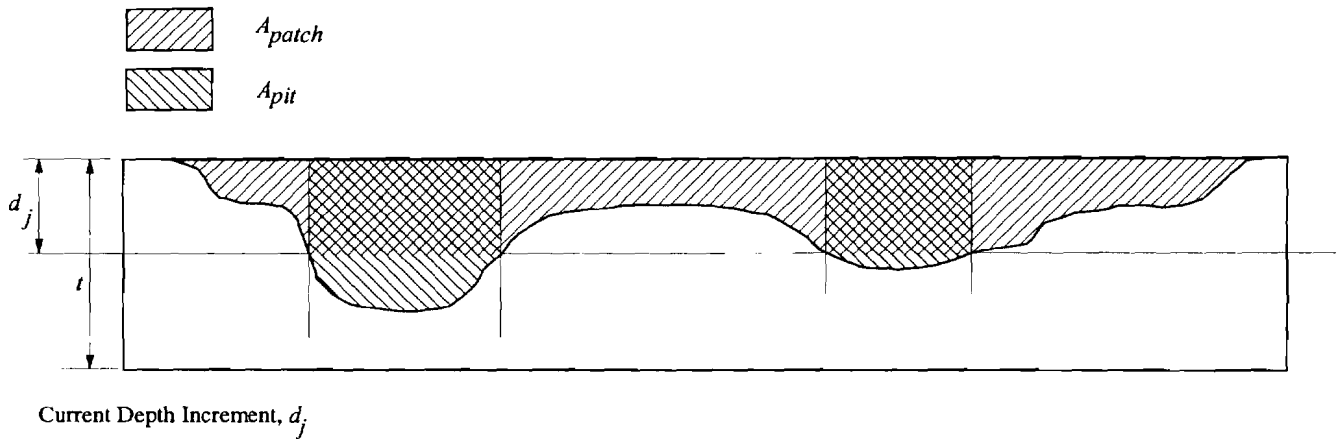


Figure 16 - Definition of A_{patch} and A_{pit} for Subdivision of Complex Shape into Idealised 'patch' and 'pits'.

Appendix A Examples for Part A

A1. Single Defect Assessment

A1.1 Example One

This example is for the assessment of an isolated corrosion defect under internal pressure loading (see Section 3.2), 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 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 $\pm 10\%$ tolerance. This sizing accuracy is quoted with a confidence level of 80%.

The maximum allowable operating pressure is 150 bar.

The Safety Class is assumed to be Normal.

From Table 2.2, Section 2.3 (assuming that the sizing accuracy follows a Normal distribution).

$$\text{StD}[d/t] = 0.08$$

Taking the partial safety factors from Table 2.3 and Table 2.4, Section 2.6 (assuming not specified supplementary requirements "U").

$$\gamma_m = 0.74$$

$$\gamma_d = 1.28$$

$$\varepsilon_d = 1.0$$

Using the procedure for assessing single defects given in Section 3.2.

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

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

$$p_{corr} = 0.74 \frac{2tSMTS}{(D-t)} \left(\frac{1 - 1.28(d/t)^*}{1 - \frac{1.28(d/t)^*}{Q}} \right) = 15.94 \text{ N/mm}^2$$

The allowable corroded pipe pressure is 15.94 N/mm² (159.4 bar). Therefore, the corrosion defect is acceptable, at the current time, for the maximum allowable operating pressure of 150 bar.

A1.2 Example Two

This example is for the assessment of an isolated corrosion defect under internal pressure loading (see Section 3.2), 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

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%.

The maximum allowable operating pressure is 150 bar.

The Safety Class is assumed to be Normal.

Assuming that the sizing accuracy follows a Normal distribution.

$$\text{StD}[t] = \frac{1.0\text{mm}}{1.28} = 0.78\text{mm}$$

$$\text{StD}[d] = \frac{1.0\text{mm}}{1.28} = 0.78\text{mm}$$

(1.0 mm is the inspection accuracy. The number 1.28 is taken from tabulated values of the standard normal distribution in a textbook for 80% confidence.

Corresponding values for 90% confidence level is ≈ 1.65 , 95% is ≈ 1.96 , 98% is ≈ 2.33 , and 99% is ≈ 2.58 . Values for

other confidence levels can be calculated as $\Phi^{-1}\left(\frac{1-x}{2}\right)$

where x is the confidence e.g. 0.80 for 80% confidence, and Φ is the standard normal distribution)

Taking the partial safety factors from Table 2.6, Section 2.7 (assuming not specified supplementary requirements "U").

$$\gamma_m = 0.77$$

$$E[t] = 19.10 \text{ mm} \quad \text{StD}[t] = 0.78 \text{ mm} \quad \text{CoV}[t] = 0.04$$

$$E[d] = 4.8 \text{ mm} \quad \text{StD}[d] = 0.78 \text{ mm} \quad \text{CoV}[d] = 0.16$$

$$(\text{CoV}[x] = \text{StD}[x]/E[x])$$

From Section 2.7:

$$E[d/t] \cong \frac{E[d]}{E[t]} = 0.25$$

$$\text{StD}[d/t] = E[d/t] \sqrt{(\text{CoV}(d)^2 + 1)(\text{CoV}(t)^2 + 1) - 1} = 0.0422$$

Taking the partial safety factors from Table 2.5, Section 2.6.

$$\gamma_d = 1 + 4.6 \text{StD}[d/t] - 13.9 \text{StD}[d/t]^2 = 1.17$$

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$$\varepsilon_d = -1.33 + 37.5 \text{StD}[d/t] - 104.2 \text{StD}[d/t]^2 = 0.07$$

Using the procedure for assessing single defects given in Section 3.2.

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

$$(d/t)^* = 0.25 + 0.07 \times 0.04 = 0.2546$$

$$P_{corr} = 0.77 \frac{2tSMTS}{(D-t)} \frac{(1 - 1.17(d/t)^*)}{\left(1 - \frac{1.17(d/t)^*}{Q} \right)} = 17.76 \text{ N/mm}^2$$

The allowable corroded pipe pressure is 17.76 N/mm² (177.6 bar). Therefore, the corrosion defect is acceptable, at the current time, for the maximum allowable operating pressure of 150 bar.

A1.3 Example Three

This example is for the assessment of an isolated longitudinal corrosion defect under internal pressure loading and superimposed longitudinal compressive stresses (see Section 3.3).

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 pipe is subject to a compressive longitudinal stress of magnitude 200 N/mm².

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%.

The maximum allowable operating pressure is 150 bar.

The Safety Class is assumed to be Normal.

From Table 2.2, Section 2.3 (assuming that the sizing accuracy follows a Normal distribution).

$$\text{StD}[d/t] = 0.08$$

Taking the partial safety factors from Table 2.3 and Table 2.4, Section 2.6 (assuming not specified supplementary requirements "U"), and from Table 2.9, Section 2.9.

$$\gamma_m = 0.74$$

$$\gamma_d = 1.28$$

$$\varepsilon_d = 1.0$$

$$\xi = 0.85$$

Using the procedure for assessing single defects given in Section 3.2.

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

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

$$P_{corr} = 0.74 \frac{2tSMTS}{(D-t)} \frac{(1 - 1.28(d/t)^*)}{\left(1 - \frac{1.28(d/t)^*}{Q} \right)} = 8.34 \text{ N/mm}^2$$

Using the procedure for assessing single defects given in Section 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 - Calculate the allowable corroded pipe pressure, including the correction for the influence of compressive stresses:

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

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

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

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

$$H_1 = \frac{1 + \frac{\sigma_L}{0.85 SMTS} \frac{1}{A_r}}{1 - \frac{0.74}{2 \times 0.85 A_r} \frac{(1 - 1.28(d/t)^*)}{\left(1 - \frac{1.28(d/t)^*}{Q} \right)}} = 0.4711$$

$$P_{corr,comp} = 0.74 \frac{2tSMTS}{(D-t)} \frac{(1 - 1.28(d/t)^*)}{\left(1 - \frac{1.28(d/t)^*}{Q} \right)} H_1 = 3.93 \text{ N/mm}^2$$

The allowable corroded pipe pressure is 3.93 N/mm² (39.3 bar). This is less than the maximum allowable operating pressure of 150 bar. Therefore the pipeline must be downrated to 39 bar, until the corrosion defect is repaired.

A2. Interacting Defects

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)

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%.

The maximum allowable operating pressure is 150 bar.

The Safety Class is assumed to be High.

From Table 2.1, Section 2.3 (assuming that the sizing accuracy follows a Normal distribution).

$$\text{StD}[d/t] = 0.08$$

Taking the partial safety factors from Table 2.3 Table 2.1, Section 2.6 (assuming not specified supplementary requirements "U").

$$\begin{aligned} \gamma_m &= 0.70 \\ \gamma_d &= 1.32 \\ \epsilon_d &= 1.0 \end{aligned}$$

Using the procedure for assessing interacting defects given in Section 4:

The defects should be grouped into axial projections as described in Steps 1 to 5 of Section 4.2.

Step 6 is to estimate the failure pressure of both defects, when treated as isolated defects. The allowable corroded pipe pressures are 16.47 N/mm² and 16.19 N/mm² respectively.

Applying the rules for defect interactions in Steps 7 to 9 (Section 8) gives:

$$\begin{aligned} \text{Combined length (Step 7)} &= 450 \text{ mm} \\ \text{Effective depth (Step 8)} &= 0.19t \end{aligned}$$

Assuming that the defect depth measurements are fully correlated:

$$\text{StD}[d_{nm}/t] = \text{StD}[d/t] = 0.08$$

Taking the partial safety factors from Table 2.3 and Table 2.4, Section 2.6 (assuming not specified supplementary requirements "U").

$$\begin{aligned} \gamma_m &= 0.70 \\ \gamma_d &= 1.32 \\ \epsilon_d &= 1.0 \end{aligned}$$

$$\text{Allowable corroded pipe pressure (Step 9)} = 14.50 \text{ N/mm}^2$$

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

The allowable corroded pipe pressure is 14.50 N/mm² (145.0 bar). This is less than the maximum allowable operating pressure of 150 bar. Therefore the pipeline must be downrated to 145 bar, until the corrosion defects are repaired.

Guidance note:

The calculated allowable corroded pipe pressure will be different if it is assumed that the depth measurements are uncorrelated, because $\text{StD}[d_{nm}/t]$ will be different.

Assuming that the defect depth measurements are uncorrelated:

$$\text{StD}[d_{nm}/t] = \frac{\sqrt{\sum_{i=1}^m l_i^2}}{l_{nm}} \text{StD}[d/t] = 0.0444$$

Taking the partial safety factors from Table 2.3 Section 2.6 (assuming not specified supplementary requirements "U").

$$\gamma_m = 0.70$$

Taking the partial safety factors from Table 2.5, Section 2.6.

$$\gamma_d = 1 + 4.3 \text{StD}[d_{nm}/t] - 4.1 \text{StD}[d_{nm}/t]^2 = 1.18$$

$$\epsilon_d = -1.33 + 37.5 \text{StD}[d_{nm}/t] - 104.2 \text{StD}[d_{nm}/t]^2 = 0.13$$

$$\text{Allowable corroded pipe pressure (Step 9)} = 16.20 \text{ N/mm}^2$$

Step 10 is to select the minimum allowable corroded pipe pressure of the individual and combined defects as the allowable corroded pipe pressure. In this case, the allowable corroded pipe pressure of the combined defect is slightly greater than that of one of the single defects, which indicates that the defects do not interact.

The allowable corroded pipe pressure is 16.19 N/mm² (161.9 bar), if it is assumed that the depth measurements are uncorrelated.

---e-n-d---o-f---Guidance note---

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A3. Complex Shaped Defect

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	=	517.1 N/mm ² (X60)

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 maximum allowable operating pressure is 70 bar.

The Safety Class is assumed to be Normal.

The defect profile is shown in Figure A1 and the defect depths are tabulated in Table A1. It is assumed that the depth measurements are fully correlated.

Table A1 Tabulated Profile for Actual Corrosion Defect.	
<i>LENGTH</i> (mm)	<i>DEPTH</i> (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 single defects given in Section 3.

Total length	=	289.0 mm
Maximum depth	=	2.8 mm

Assuming that the sizing accuracy follows a Normal distribution. (The number 1.645 is taken from tabulated values of the normal distribution in a textbook (90%)).

$$StD[t] = \frac{0.1 \text{ mm}}{1.65} = 0.06 \text{ mm}$$

$$StD[d] = \frac{0.1 \text{ mm}}{1.65} = 0.06 \text{ mm}$$

Taking the partial safety factors from Table 2.6, Section 2.7 (assuming not specified supplementary requirements "U").

$$\gamma_m = 0.77$$

$$E[t] = 8.20 \text{ mm} \quad StD[t] = 0.06 \text{ mm} \quad CoV[t] = 0.007$$

$$E[d] = 2.8 \text{ mm} \quad StD[d] = 0.06 \text{ mm} \quad CoV[d] = 0.022$$

$$(CoV[x] = StD[x]/E[x])$$

From Section 2.7:

$$E[d/t] \cong \frac{E[d]}{E[t]} = 0.3415$$

$$StD[d/t] = E[d/t] \sqrt{(CoV(d)^2 + 1)(CoV(t)^2 + 1) - 1} = 0.0078$$

Taking the partial safety factors from Table 2.5, Section 2.6.

$$\gamma_d = 1 + 4.6 StD[d/t] - 13.9 StD[d/t]^2 = 1.035$$

$$\varepsilon_d = -1.33 + 37.5 StD[d/t] - 104.2 StD[d/t]^2 = 0.0$$

$$\text{Allowable Corroded Pipe Pressure} = 8.17 \text{ N/mm}^2$$

If this complex shaped defect is assessed as a single defect, based on the total length and maximum depth, then the allowable corroded pipe pressure is 8.17 N/mm².

Using the procedure for assessing complex shaped defects given in Section 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 allowable corroded pipe pressure of the defect from the average depth and the total length.

Assuming that the defect depth measurements are fully correlated:

$$StD[d_{ave}/t] = StD[d/t] = 0.0075$$

Taking the partial safety factors from Table 2.5, Section 2.6, and Table 2.6, Section 2.7 (assuming not specified supplementary requirements "U").

$$\gamma_m = 0.77$$

$$\gamma_d = 1.034$$

$$\varepsilon_d = 0.0$$

$$\text{Allowable Corroded Pipe Pressure} = 9.54 \text{ N/mm}^2$$

Progressive Depth Analysis (Steps 3 to 15)

The profile was sectioned at 50 levels and the allowable corroded pipe pressure was estimated for each increment. Figure A2 shows the variation of the allowable corroded pipe pressure estimate with depth. The minimum allowable corroded pipe pressure estimate was 9.19 N/mm^2 (91.9 bar). The section depth was 1.06 mm, which corresponds to the natural division between patch and pit, which can be seen in Figure A1. The effect of the relatively distinct change in profile at this depth produces a sharp change in the estimated allowable corroded pipe pressure curve, as shown in Figure A2.

The calculations at the section which produced the minimum allowable corroded pipe 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

Assuming that the defect depth measurements are fully correlated:

$$\text{StD}[d_{\text{patch}}/t] = \text{StD}[d/t] = 0.0075$$

Taking the partial safety factors from Table 2.5, Section 2.6, and Table 2.6, Section 2.7 (assuming not specified supplementary requirements "U").

$$\gamma_m = 0.77$$

$$\gamma_d = 1.034$$

$$\epsilon_d = 0.0$$

Patch allowable corroded pipe pressure (Step 5)	=	9.99 N/mm ²
Patch capacity pressure (Step 5)	=	14.20 N/mm ²
Effective reduced thickness (Step 7)	=	7.60 mm

Steps 6 to 12 are to estimate the allowable corroded pipe pressure of the idealised pits.

Step 9 is to estimate the allowable corroded pipe pressure of all individual idealised pits.

Step 12 is to estimate the allowable corroded pipe pressure of the combined defect from n to m .

$$\text{Number of Pits} = 1$$

Pit	Average Depth (mm)	Average Depth On Reduced Wall (mm)	Length (mm)	Failure Pressure (N/mm ²)
1	1.70	1.10	222	9.19

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

$$\text{Minimum allowable corroded pipe pressure (Step 13)} = 9.19 \text{ N/mm}^2.$$

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 8.17 N/mm^2 (81.7 bar).

Step 16 is to estimate the allowable corroded pipe 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 A2), but not less than the pressure from step 15.

Analysis of the defect as a complex profile, using the progressive depth method, gives an allowable corroded pipe pressure estimate of 9.19 N/mm^2 .

The allowable corroded pipe pressure is 9.19 N/mm^2 (91.9 bar), if it is assumed that the depth measurements are fully correlated. Therefore, the corrosion defect is acceptable, at the current time, for the maximum allowable operating pressure of 70 bar.

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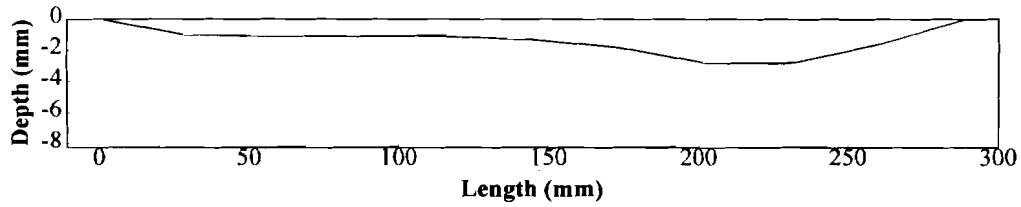


Figure A1 Profile for Actual Corrosion Defect - Example Assessment.

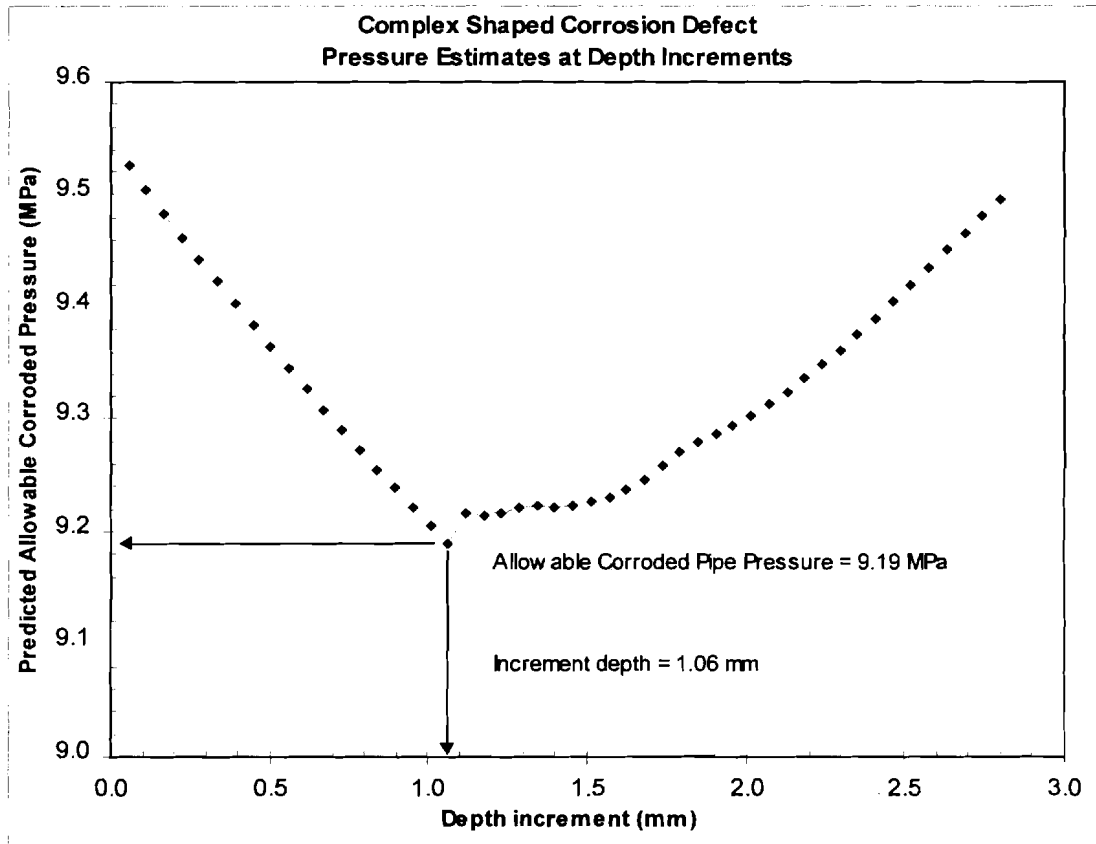


Figure A2 Variations of the Estimated Failure Pressure for Actual Corrosion Defect - Example Assessment.

Appendix B Examples for Part B

B1. Single Defect Assessment

B1.1 Example One

This example is for the assessment of an isolated corrosion defect under internal pressure loading only (see Section 7.2).

The dimensions and material properties are summarised as follows:

Outside Diameter	=	812.8 mm
Original Wall Thickness	=	19.10 mm
Measured UTS	=	608.5 N/mm ²
Defect Length (max)	=	203.2 mm
Defect Depth (max)	=	13.4 mm

Using the procedure for assessing single defects given in Section 7.2.

Step 1 - Calculate the failure pressure using:

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

$$P_f = \frac{2tUTS}{(D-t)} \frac{\left(1 - \frac{d}{t}\right)}{\left(1 - \frac{d}{tQ}\right)} = 18.17 \text{ N/mm}^2$$

(This compares with a burst pressure of 20.50 N/mm² from a full scale test).

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

$$P_{sw} = (0.9)(0.72)P_f = 11.77 \text{ N/mm}^2$$

The safe working pressure is 11.77 N/mm².

B1.2 Example Two

This example is for the assessment of an isolated corrosion defect under internal pressure and compressive longitudinal loading (see Section 7.3).

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 pipe is subject to a compressive longitudinal stress of magnitude 200 N/mm².

Using the procedure for assessing single defects given in Section 7.

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:

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

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

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

The safe working pressure is 16.04 N/mm².

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B2. Interacting Defects

B2.1 Example One

This example is for a pair of rectangular patches 203.2 mm in length and separated axially by 81.3mm. 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
Measured UTS	=	624.2 N/mm ²

Using the procedure for assessing interacting defects given in Section 8:

The defects should be grouped into axial projections as described in Steps 1 to 5 of Section 8.2.

Step 6 is to estimate the failure pressure of both defects, when treated as isolated defects. These pressures are 19.73 N/mm² and 20.59 N/mm² respectively.

Applying the rules for defect interactions in Steps 7 to 9 (Section 8) 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 predicted failure pressure of the defect is therefore 17.71 N/mm².

(In a full scale test, the recorded failure pressure of this defect was 19.60 N/mm²).

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/mm².

B2.2 Example Two

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
Measured UTS	=	624.2 N/mm ²

Using the procedure for assessing interacting defects given in Section 8:

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/mm² and 19.73 N/mm² respectively.

Applying the rules for defect interactions in Steps 7 to 9 (Section 8) 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/mm².

(In a full scale test, the recorded failure pressure of this defect was 22.20 N/mm²).

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/mm².

B3. Complex Shaped Defect

B3.1 Example One

This example is an analysis of the failure pressure of a complex shaped defect (see Section 9). The defect is a machined defect. 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 B1 :

Outside Diameter	=	762.0 mm
Original Wall Thickness	=	22.1 mm
Measured UTS	=	525.3 N/mm ²

The defect profile is shown in Figure B1 and the exact depths are tabulated in Table B1.

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
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
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

Single Defect Solution (Steps 1 to 2)

$$\begin{aligned} \text{Total length} &= 572.0 \text{ mm} \\ \text{Maximum depth} &= 17.1 \text{ mm} \end{aligned}$$

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

$$\begin{aligned} \text{Total projected area loss} &= 7584.6 \text{ mm}^2 \\ \text{Average depth} &= 13.26 \text{ mm} \end{aligned}$$

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

$$\text{Failure pressure} = 16.23 \text{ N/mm}^2$$

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 B2.

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:

$$\begin{aligned} \text{Depth of increment no. 12} &= 4.1 \text{ mm} \\ \text{Patch average area (Step 4)} &= 2347 \text{ mm}^2 \\ \text{Patch length} &= 572.0 \text{ mm} \\ \text{Patch average depth (Step 4)} &= 4.1 \text{ mm} \\ \text{Patch failure pressure (Step 5)} &= 27.47 \text{ N/mm}^2 \end{aligned}$$

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

$$\text{Number of Pits} = 1$$

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

$$\text{Effective reduced thickness} = 19.42 \text{ mm}$$

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:

$$\text{Minimum pressure} = 15.54 \text{ N/mm}^2$$

Using the procedure for assessing complex shaped defects given in Section 9:

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Depth of increment no. 38 = 13.0 mm
 (This is the section that gives the minimum pressure).
 Patch average area (Step 4) = 7019 mm²
 Patch length (Step 4) = 572.0 mm
 Patch average depth (Step 4) = 12.59 mm
 Patch failure pressure (Step 5) = 17.65 N/mm²
 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/mm²

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 Section 7.2.

Total length = 572.0 mm
 Maximum depth = 17.1 mm
 Failure pressure = 10.03 N/mm²

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/mm².

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 B2).

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/mm² from a section depth of 13.0 mm. This compares with an actual failure pressure of 13.68 N/mm².

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:

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

The safe working pressure is 8.68 N/mm² (86.8 bar).

B3.2 Example Two

The following worked example is based on a pressure test to failure on a pipe section containing an actual corrosion defect.

The pipeline geometry and properties are summarised as follows:

Outside Diameter = 611.0 mm
 Wall Thickness = 8.20 mm
 UTS = 571.0 N/mm²

The defect profile is shown in Figure B3 and the exact depths are tabulated in Table B2.

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 Section 9:

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 mm²
 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/mm²

Progressive Depth Analysis (Steps 3 to 16)

The profile was sectioned at 50 levels and the failure pressure estimated for each increment. Figure B4 shows the variation of the failure pressure estimate with depth. The minimum failure pressure estimate was 13.21 N/mm². The

section depth was 1.09 mm; this corresponds to the natural division between patch and pit, which can be seen in Figure B4. 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 B4.

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/mm²

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 B4).

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/mm².

The actual burst pressure of the pipe containing the defect was 15.40 N/mm².

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 Section 7.

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/mm².

Step 16 is to estimate the allowable corroded pipe 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.

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:

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

The safe working pressure is 8.56 N/mm² (85.6 bar).

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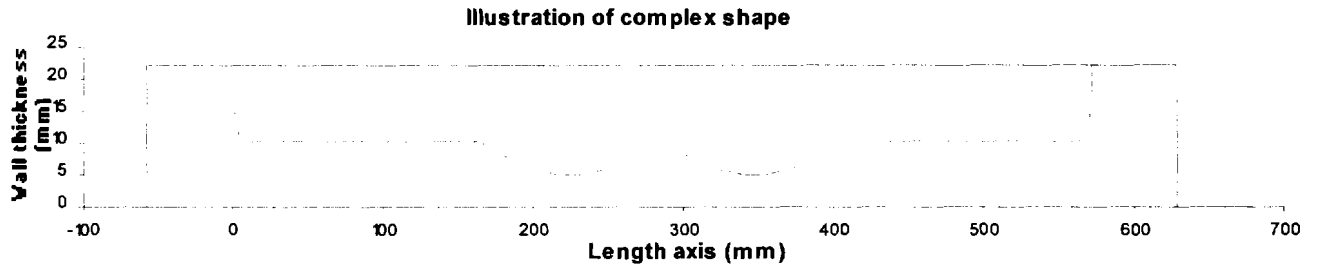


Figure B1 Profile for Complex Shaped Defect - Example Assessment.

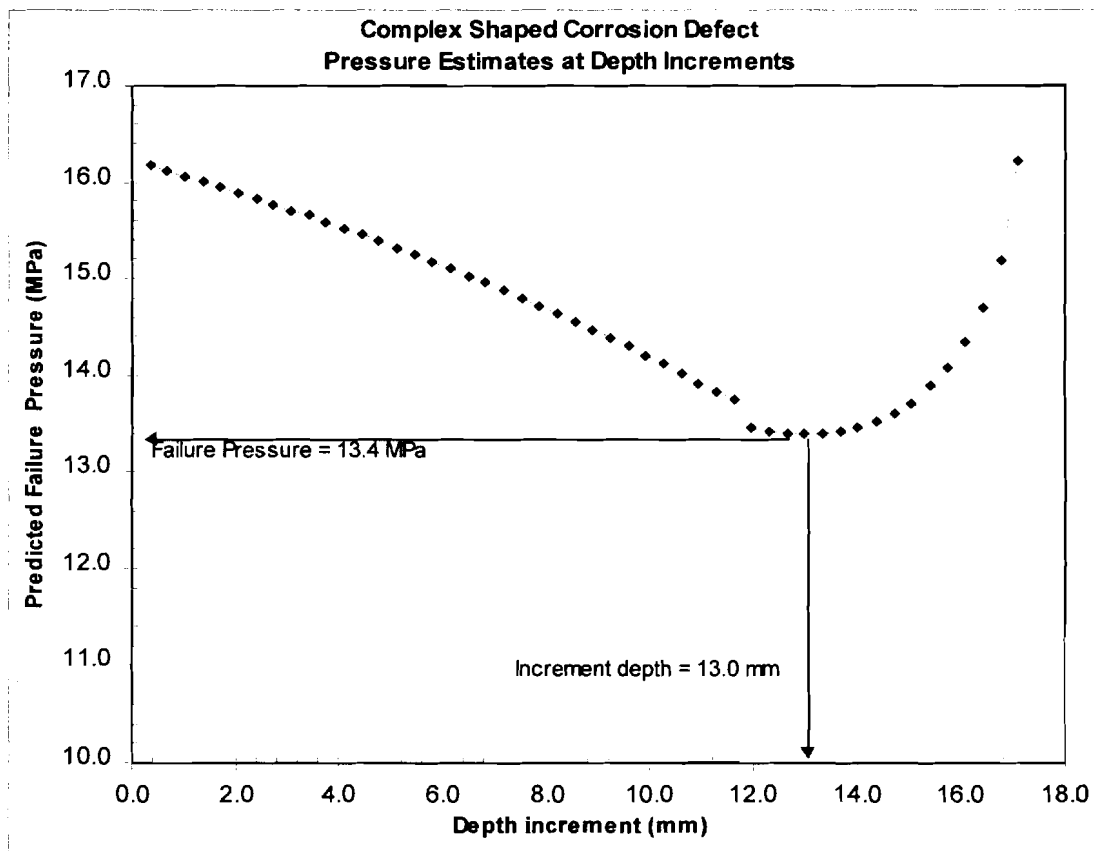


Figure B2 Variations of the Estimated Failure Pressure for Complex Shaped Defect - Example Assessment.

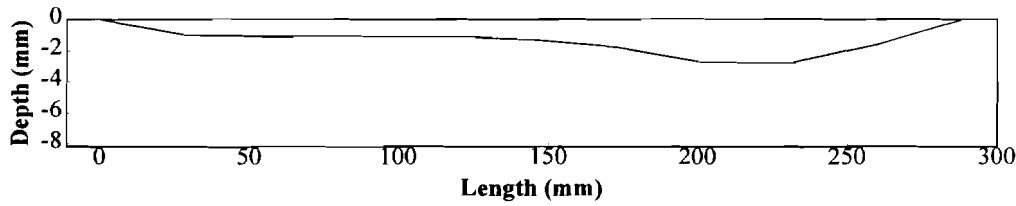


Figure B3 Profile for Actual Corrosion Defect - Example Assessment.

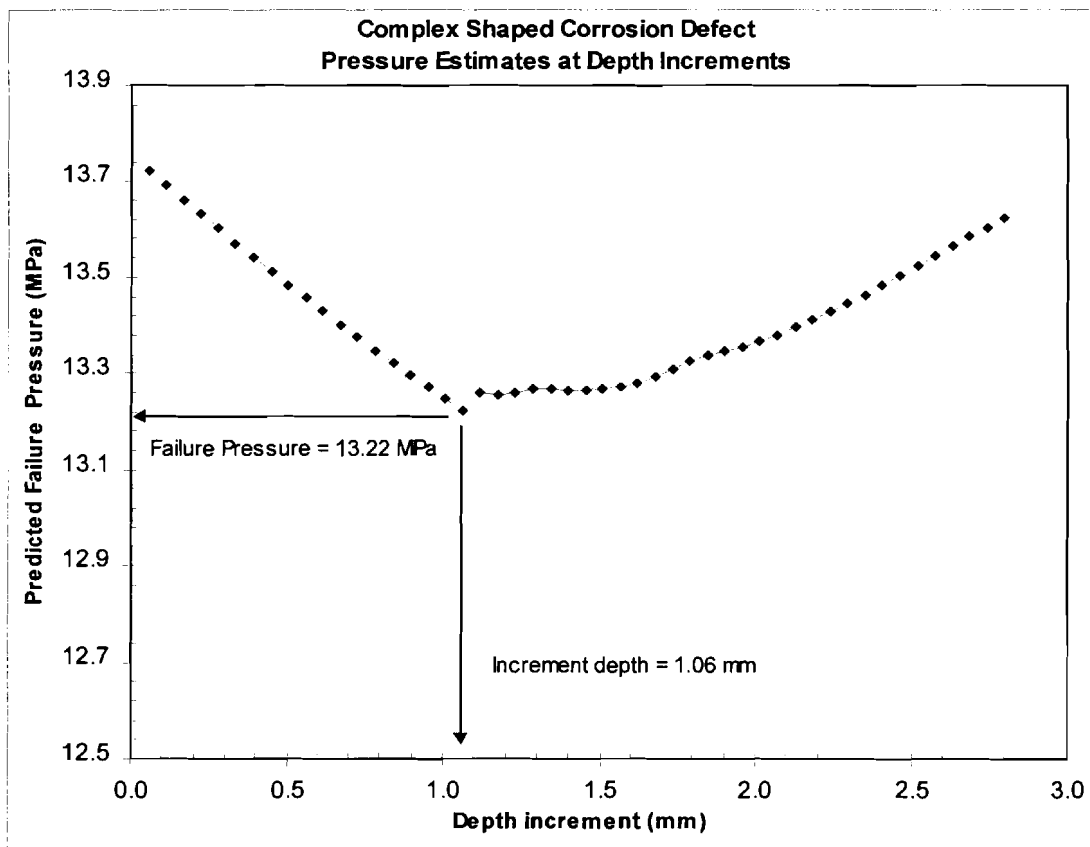


Figure B4 Variations of the Estimated Failure Pressure for Actual Corrosion Defect - Example Assessment.

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Appendix C Correlated and uncorrelated Measurements of Wall Thickness loss

C1. 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 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 error would be the 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 would 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 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 would 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.

C2. 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

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

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

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

where $Z_1 = \ln(r)$ and $Z_2 = \ln(t)$

The mean value and standard deviation for Z_1 and Z_2 may be derived from:

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

$$E[Z_1] = \ln(E[r]) - 0.5\text{StD}[Z_1]^2$$

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

$$E[Z_2] = \ln(E[t]) - 0.5\text{StD}[Z_2]^2$$

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 , $\rho_{Z_1 Z_2}$, may be calculated from:

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

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

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

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

where $Z_1 = \ln(r)$ and $Z_2 = \ln(t)$.

The mean value and standard deviation for Z_1 and Z_2 may be derived from:

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

$$E[Z_1] = \ln(E[d]) - 0.5 \text{StD}[Z_1]^2$$

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

$$E[Z_2] = \ln(E[t]) - 0.5 \text{StD}[Z_2]^2$$

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 , ρ_{Z_1, Z_2} , may be calculated from:

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

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Appendix D The assessment of single defects subject to internal pressure plus bending loads and/or tensile longitudinal loads

D1. Introduction

The method outlined in this Appendix for the assessment of single defects subject to internal pressure plus bending loads and/or tensile longitudinal loads, is based upon the plastic collapse solutions recommended in PD6493 (ref. /6/) and R6 (ref. /12/) for the global plastic collapse of pressurised pipes containing part thickness and part circumferential defects subject to bending and/or tensile longitudinal loads. These approaches have been integrated into the procedures described in the main body of the document for the convenience of users of this document who may wish to consider bending and/or tensile longitudinal loads.

D2. Requirements

For corrosion defects to be assessed as a single defect (see Figure 6), the defect must be clearly defined as an isolated defect without any adjacent defects with which it may interact. This requirement can be assessed from Section 7.1.

D3. 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):

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

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}):

$$P_{sw} = F P_f$$

D4. Safe Working Pressure Estimate - Internal Pressure and Combined Loading

The correction for combined tensile longitudinal and bending loads is based upon a global plastic collapse solution for surface circumferential defects under bending and internal pressure loading. The plastic collapse solution has been validated for crack-like defects, but has not been validated for corrosion damage in large diameter pipeline materials (ref. /13/).

The validation of the method for assessing corrosion defects under internal pressure and combined longitudinal and bending loads is not as comprehensive as the validation of the method for assessing corrosion defects under internal pressure loading only.

The safe working pressure of a single defect subject to internal pressure and longitudinal and/or bending 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 longitudinal and/or bending loads on the failure pressure of the single defect (see Figure 7).

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

$$\sigma_1 < \sigma_L < \sigma_2$$

where:

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

$$\sigma_2 = UTS \left[K - 0.5 \frac{\left(1 - \frac{d}{t}\right)}{\left(1 - \frac{d}{tQ}\right)} \right]$$

where:

$$K = \min(K_1, K_2)$$

$$K_1 = A_r \frac{1+YT}{2} \quad \text{or} \quad \left(1 - \frac{d}{t}\theta\right) \left(\frac{1+YT}{2}\right) \quad \text{if the exact area reduction is not known}$$

$$K_2 = \frac{4}{\pi} \left(\frac{1+YT}{2}\right) \left\{ \cos \left[\frac{d}{2t} \theta \pi \right] - \frac{d}{2t} \sin(\theta \pi) \right\}$$

$$= \frac{4}{\pi} \left(\frac{1+YT}{2}\right) \left\{ \left(1 - \frac{d}{t}\right) \sin \left[\frac{\pi}{2} \left(\frac{1 - \frac{d}{t}\theta}{1 - \frac{d}{t}} \right) \right] + \frac{d}{2t} \sin \left[\frac{\pi}{2} \left(\frac{1 - \frac{d}{t}\theta}{1 - \frac{d}{t}} \right) \right] \right\}$$

If the above condition is satisfied then STEPS 4 and 5 can be neglected.

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

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

where:

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

STEP 4 If the combined longitudinal stresses are compressive, then estimate the failure pressure for a longitudinal break including the correction for the influence of compressive stresses (see Figure 4).

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

where:

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

STEP 5 If the combined longitudinal stresses are tensile then estimate the failure pressure for a circumferential break (see Figure 4).

$$P_{tensile} = \frac{2tUTS}{(D-t)} H_2$$

where:

$$H_2 = (1+YT) \left\{ \left(1 - \frac{d}{t}\theta\right) - \frac{\sigma_A}{\sigma_F} - \frac{2}{\pi} \sin^{-1} \left[\frac{\sigma_B}{\sigma_F} \frac{\pi}{4} + \frac{d}{2t} \sin(\theta \pi) \right] \right\}$$

$$\text{for } \theta \geq \frac{1}{\pi} \sin^{-1} \left[\frac{\sigma_B}{\sigma_F} \frac{\pi}{4} \frac{2}{2 - \frac{d}{t}} \right]$$

and

$$H_2 = (1+YT) \left\{ \left(1 - \frac{d}{t}\theta\right) - \frac{\sigma_A}{\sigma_F} - \frac{2}{\pi} \left(1 - \frac{d}{t}\right) \sin^{-1} \left[\frac{\left(\frac{\sigma_B}{\sigma_F} \frac{\pi}{4} - \frac{d}{2t} \sin(\theta \pi) \right)}{\left(1 - \frac{d}{t}\right)} \right] \right\}$$

$$\text{for } \theta < \frac{1}{\pi} \sin^{-1} \left[\frac{\sigma_B}{\sigma_F} \frac{\pi}{4} \frac{2}{2 - \frac{d}{t}} \right]$$

STEP 6 The failure pressure of single corrosion defect subjected to internal pressure loading combined with superimposed longitudinal stresses is the minimum of P_{press} , P_{comp} and $P_{tensile}$:

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

STEP 7 Calculate the safe working pressure of the corroded pipe (P_{sw}):

$$P_{sw} = F P_f$$