

RECOMMENDED PRACTICE
DNV-RP-F101

CORRODED PIPELINES

OCTOBER 2010

DET NORSKE VERITAS

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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.

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- Statoil
- Total Oil Marine plc

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CHANGES

• General

As of October 2010 all DNV service documents are primarily published electronically.

In order to ensure a practical transition from the “print” scheme to the “electronic” scheme, all documents having incorporated amendments and corrections more recent than the date of the latest printed issue, have been given the date October 2010.

An overview of DNV service documents, their update status and historical “amendments and corrections” may be found through http://www.dnv.com/resources/rules_standards/.

• Main changes

Since the previous edition (October 2004), this document has been amended, most recently in October 2006. All changes have been incorporated and a new date (October 2010) has been given as explained under “General”.

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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, includes calibrated safety factors taking into account the natural spread in material properties and wall thickness and internal pressure variations. Uncertainties associated with the sizing of the defect and the specification of the material properties are specifically considered in determination of the allowable operating pressure. This part of the RP is also a supplement to DNV-OS-F101. 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 Update year 2004

The RP was first issued in 1999 and updated in 2004 (this version). The update is based on experience and feedback from four years of use.

The update covers:

- Sec.3 (previously Sec.2) concerning Part A safety factors has been rewritten and a simplified approach for considering the inspection accuracy is given
- a new section describing the methodology and the simplified capacity equation is included
- recommended limitations for Charpy values are included
- a recommendation for probabilistic calculations is included
- recommendations for temperature de-rating for SMYS and SMTS are included.

The update includes the following few technical corrections of which the user should be aware:

- the calculation of fully correlated depth measurement for interaction defects Part A (*Step 9* in Sec.5.2 and *Step 12* in Sec.6) is modified, and is less strict (the 1999 version is conservative)
- UTS in Part B is changed to SMTS and “ f_u ”.

1.3 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.

1.4 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 DNV-OS-F101 Submarine Pipeline Systems, /8/, /9/ or other recognised pipeline design code as e.g. 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 in the design code is not 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.

1.5 Structure of RP

The RP describes two alternative approaches. The first approach is given in Part A, which consists of Sec.3 through Sec.6. The second approach is given in Part B, which consists of Sec.7 through Sec.10.

A flow chart describing the assessment procedure (for both Part A and Part B) is shown in Fig.1-1.

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

1.6 Applicable defects

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

- Internal corrosion in the base material.
- External corrosion in the base material.
- Corrosion in seam welds.
- Corrosion in girth welds.
- Colonies of interacting corrosion defects.
- Metal loss due to grind repairs (provided that the grinding leaves a defect with a smooth profile, and that the removal of the original defect has been verified using appropriate NDT methods).

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

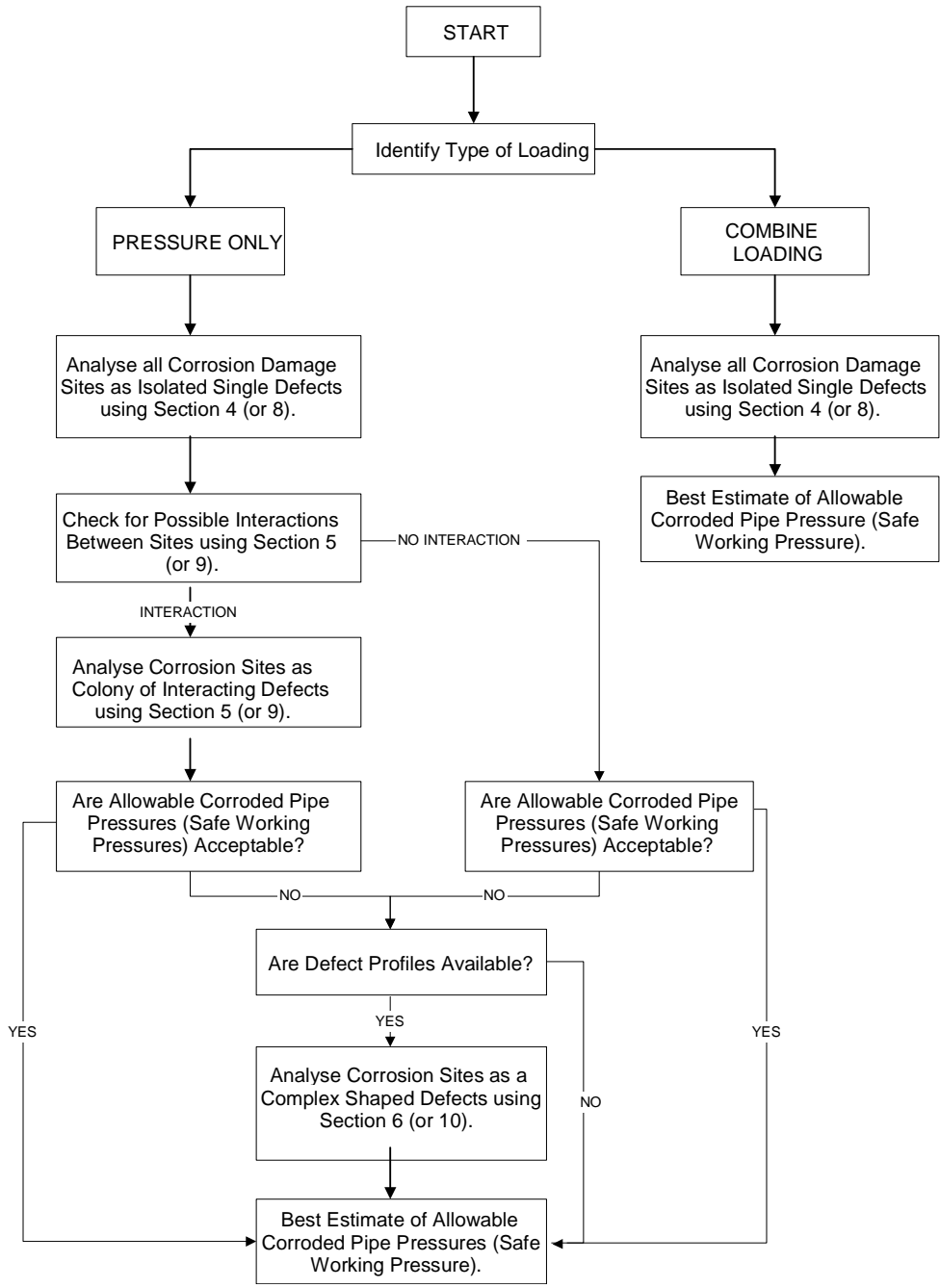


Figure 1-1
Flowchart of the assessment procedure

1.7 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:

- Single defect.
- Interacting defects.
- Complex shaped defects.

Internal pressure loading and combined with longitudinal compressive stresses for:

- Single defects.

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

The 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/).

1.8 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).

The assessment procedure is only applicable to linepipe steels that are expected to fail through plastic collapse. Modern pipeline steel materials normally have sufficient toughness to expect plastic collapse failure. Studies have recommended Charpy V-notch value as lower bound for the material toughness for plastic collapse /18/ and /19/.

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

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

- 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.

1.9 Other failure modes

Other failure modes, such as buckling, wrinkling, fatigue and fracture, may need to be considered. These failure modes are not addressed in this document, and other methods may be applicable, ref. /6/, /12/ and /14/.

1.10 Tiered approach and further assessment

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

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

Furthermore, if the corrosion defects are still not found to be acceptable using the procedures given in this RP, the user has the option of considering an alternative course of action to more accurately assess the remaining strength of the corroded pipeline. This could include, but is not limited to, detailed finite element analysis, probabilistic assessments and/or full

scale testing, and is outside the scope of this document. If an alternative course is selected, the user should document the reliability of the results, and this can often be a very challenging task.

1.11 Responsibility

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

1.12 Validation

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

Pipeline:

Pipe Diameter, mm	219.1 (8")	to	914.4 (36")
Wall Thickness, mm	3.40	to	25.40
D/t ratio	8.6	to	149.4
Grade (API/5L)	X42	to	X65

Defects:

d/t	0	to	0.97
l/(Dt) ^{0.5}	0.44	to	35
c/t (circumferential)	0.01	to	22

(Shortest defect was $l = 2.1$ t)

For nomenclature, see Sec.1.14.

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

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

The validation of the methods described in this document for the assessment of corrosion defects subject to internal pressure loading plus compressive longitudinal stress (see Sec.4.3 and 4.4, is not as comprehensive as the validation of the methods for the assessment of corrosion defects subject to internal pressure loading alone.

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

1.13 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.

1.14 Symbols and abbreviations

A	=	Projected area of corrosion in the longitudinal plane through the wall thickness (mm^2).	Z	=	Circumferential angular spacing between projection lines (degrees).
A_c	=	Projected area of corrosion in the circumferential plane through the wall thickness (mm^2).	$E[X]$	=	Expected value of random variable X.
$A_{i,\text{pit}}$	=	Area of the 'i'th idealised 'pit' in a complex shaped defect (mm^2).	$\text{StD}[X]$	=	Standard deviation of random variable X.
A_{patch}	=	Area of an idealised 'patch' in a complex shaped defect (mm^2).	$\text{CoV}[X]$	=	Coefficient of variation of random variable X.
A_r	=	Circumferential area reduction factor.		=	$\text{StD}[X]/E[X]$
	=	$1 - A_c/\pi Dt$	$(X)^*$	=	Characteristic value of X.
	\approx	$1 - (d/t)\theta$	X_M	=	Model uncertainty factor
D	=	Nominal outside diameter (mm).	c	=	Circumferential length of corroded region (mm).
F	=	Total usage factor.	d	=	Depth of corroded region (mm).
	=	$F_1 F_2$	d_{ave}	=	Average depth of a complex shaped defect (mm).
F_1	=	Modelling factor.		=	A/l_{total}
F_2	=	Operational usage factor.	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).
F_X	=	External applied longitudinal force (N).	$d_{e,\text{nm}}$	=	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).
H_1	=	Factor to account for compressive longitudinal stresses.	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).
H_2	=	Factor to account for tensile longitudinal stresses.	d_j	=	The 'j'th depth increment in a progressive depth analysis of a complex shaped defect (mm).
M_Y	=	External applied bending moment (Nmm).	d_{nm}	=	Average depth of a defect combined from adjacent defects n to m in a colony of interacting defects (mm).
N	=	Number of defects in a colony of interacting defects.	d_{patch}	=	Average depth of an idealised 'patch' in a complex shaped defect (mm).
P_{comp}	=	Failure pressure of the corroded pipe for a single defect subject to internal pressure and compressive longitudinal stresses (N/mm^2).	$(d/t)_{\text{meas}}$	=	Measured (relative) defect depth
P_f	=	Failure pressure of the corroded pipe (N/mm^2).	$(d/t)_{\text{meas,acc}}$	=	Maximum acceptable measured (relative) defect depth
P_{f_j}	=	Failure pressure for 'j'th depth increment in a progressive depth analysis of a complex shaped defect (N/mm^2).	f_u	=	Tensile strength to be used in design
P_{nm}	=	Failure pressure of combined adjacent defects n to m, formed from a colony of interacting defects (N/mm^2).	f_y	=	Yield strength to be used in design
P_{patch}	=	Failure pressure of an idealised 'patch' in a complex shaped defect (N/mm^2).	i	=	Isolated defect number in a colony of N interacting defects.
P_{press}	=	Failure pressure of the corroded pipe for a single defect subject to internal pressure only (N/mm^2).	j	=	Increment number in a progressive depth analysis of a complex shaped defect.
P_{sw}	=	Safe working pressure of the corroded pipe (N/mm^2).	l	=	Longitudinal length of corroded region (mm).
P_{tensile}	=	Failure pressure of the corroded pipe for a single defect subject to internal pressure and tensile longitudinal stresses (N/mm^2).	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).
P_{total}	=	Failure pressure of a complex shaped defect when treated as a single defect (N/mm^2).	l_j	=	Longitudinal length increment in a progressive depth analysis of a complex shaped defect (mm).
P_i	=	Failure pressures of an individual defect forming part of a colony of interacting defects (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).
RP	=	Recommended Practice	l_{total}	=	Total longitudinal length of a complex shaped defect (mm).
Q	=	Length correction factor.	P_{mao}	=	Maximum allowable operating pressure (N/mm^2).
Q_i	=	Length correction factor of an individual defect forming part of a colony of interacting defects.	$P_{\text{cap,patch}}$	=	Capacity pressure of an idealised 'patch' in a complex shaped defect (N/mm^2).
Q_{nm}	=	Length correction factor for a defect combined from adjacent defects n to m in a colony of interacting defects.	P_{corr}	=	Allowable corroded pipe pressure of a single longitudinal corrosion defect under internal pressure loading (N/mm^2).
Q_{total}	=	Length correction factor for the total longitudinal length of a complex shaped defect (mm).	P_{corr_j}	=	Allowable corroded pressure for 'j'th depth increment in a progressive depth analysis of a complex shaped defect (N/mm^2).
SMTS	=	Specified minimum tensile strength (N/mm^2).	$P_{\text{corr,circ}}$	=	Allowable corroded pipe pressure of a single circumferential corrosion defect (N/mm^2).
SMYS	=	Specified minimum yield stress (N/mm^2).	$P_{\text{corr,comp}}$	=	Allowable corroded pipe pressure of a single longitudinal corrosion defect under internal pressure and superimposed longitudinal compressive stresses (N/mm^2).
ULS	=	Ultimate Limit State			
UTS	=	Ultimate Tensile Strength (N/mm^2)			

P_i	=	Allowable corroded pipe pressures of individual defects forming a colony of interacting defects (N/mm^2).
P_{nm}	=	Allowable corroded pressure of combined adjacent defects n to m, formed from a colony of interacting defects (N/mm^2).
P_{patch}	=	Allowable corroded pipe pressure of an idealised 'patch' in a complex shaped defect (N/mm^2).
P_{total}	=	Allowable corroded pipe pressure of a complex shaped defect when treated as a single defect (N/mm^2).
r	=	Remaining ligament thickness (mm).
s	=	Longitudinal spacing between adjacent defects (mm).
s_i	=	Longitudinal spacing between adjacent defects forming part of a colony of interacting defects (mm).
t	=	Uncorroded, measured, pipe wall thickness, or t_{nom} (mm).
t_e	=	Equivalent pipe wall thickness used in a progressive depth analysis of a complex shaped defect (mm).
ϵ_d	=	Factor for defining a fractile value for the corrosion depth.
ϕ	=	Circumferential angular spacing between adjacent defects (degrees).
γ_d	=	Partial safety factor for corrosion depth.
γ_m	=	Partial safety factor for longitudinal corrosion model prediction.
γ_{mc}	=	Partial safety factor for circumferential corrosion model prediction.
η	=	Partial safety factor for longitudinal stress for circumferential corrosion.
θ	=	Ratio of circumferential length of corroded region to the nominal outside circumference of the pipe, ($c/\pi D$).
σ_A	=	Longitudinal stress due to external applied axial force, based on the nominal wall thickness (N/mm^2).
σ_B	=	Longitudinal stress due to external applied bending moment, based on the nominal wall thickness (N/mm^2).
σ_L	=	Combined nominal longitudinal stress due to external applied loads (N/mm^2).
σ_u	=	Ultimate tensile strength (N/mm^2).
σ_1	=	Lower bound limit on external applied loads (N/mm^2).
σ_2	=	Upper bound limit on external applied loads (N/mm^2).
ξ	=	Usage factor for longitudinal stress.

1.15 Units

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

2. Methodology

2.1 Capacity equation

The expression of the burst capacity for a single longitudinally oriented, rectangular shaped, corrosion defect was developed

based on a large number of FE analyses, and a series of full scale burst tests. By using finite element analyses the effect of each important parameter was investigated, while the accuracy of the analyses was verified by a large number of full-scale burst tests. The equations used in the development of this RP and in the calibration are fairly complex. For practical use a simplified capacity equation is give below. For more details see /16/ and /17/.

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

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

where

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

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

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

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

The factor 1.05 in the capacity equation is determined from comparison with laboratory test results with rectangular shaped metal loss defects, see /17/.

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

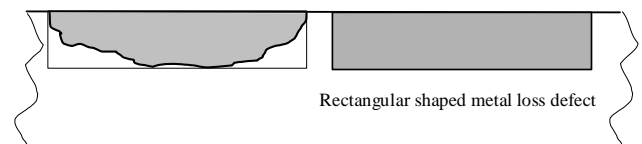


Figure 2-1
Illustration of irregular and rectangular defects

2.2 Sizing accuracy and uncertainties

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

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

For example, in an assessment of a defect only the material

grade (giving SMTS and SMYS) will usually be available. The actual material properties at the location of the defect will not be known. Furthermore, the defect sizing will be determined with some level of uncertainty. The defect can be shallower, or deeper, than the measured value, as illustrated in Fig.2-2. This depth uncertainty has to be considered in the assessment of the allowable pressure.

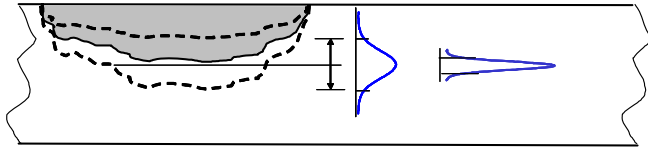


Figure 2-2
Measured defect depth and sizing accuracy

2.3 Part A, calibrated safety factors

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

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

The maximum allowable operating pressure for a pipeline with a corrosion defect is given by the acceptance equation with the safety factors:

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

where

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

The safety factors are described in Sec.3.

2.4 Part B, allowable stress approach

The approach given in Part B is based on the ASD (Allowable Stress Design) format. The failure pressure (capacity) of the pipeline with the corrosion defect is calculated, and multiplied by a safety factor to obtain a safe working pressure. Often the original design factor is used as the safety factor.

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

2.5 Onshore pipelines

Design codes for onshore pipelines allow in general a lower utilisation of the material compared to offshore codes, i.e. the safety factors are higher. These factors probably implicitly

cover other loads and degradation mechanisms than considered in this RP, and if using Part A this could be in conflict with the safety philosophy in the original design code. Part B could be more appropriate for onshore pipelines, where the user have to account for these additional failures aspects. However, when using Part B it is recommended that the user also check according to Part A. If this yields stricter results, considerations should be made.

2.6 Characteristic material properties

The 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 characteristic material properties are to be used in the assessment of the metal loss defects. The material grades refer to mechanical properties at room temperature, and possible temperature effects on the material properties should also be considered.

$f_y = SMYS - f_{y,temp}$
$f_u = SMTS - f_{u,temp}$

where

$f_{y,temp}$ and $f_{u,temp}$ = de-rating value of the yield stress and tensile strength due to temperature.

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

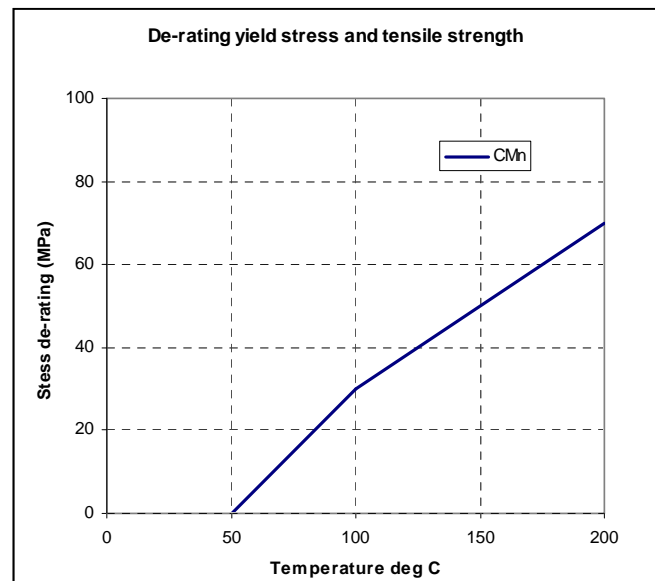


Figure 2-3
Proposed de-rating values

2.7 Pressure reference height and static head

The assessment of corrosion defects should consider the pressure load at the location of the defect, both internal and external. If this effect is not included, conservative pressure loads should be used. The pressure reference height and the elevation of the defect must be known.

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

For onshore pipelines only the internal static head is to be

included.

The calculated pressures, e.g. p_{corr} in this RP refer to the local differential pressure load, and when determining p_{mao} (MAOP) the internal and external static head should be included.

2.8 Probabilistic assessments

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

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

Probabilistic assessment is outside the scope of this RP, and the rest of Sec.2.8 is given for information only.

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

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

where

P_{cap} = the burst pressure capacity, but where the 1.05 factor is replaced by X_M

P_{INT} = the annual maximum differential pressure.

The parameters in the limit state should be modelled with their actual distributions, and considerations should be given to the inspection sizing accuracy. A set of input parameter distributions considered to be representative for pipelines were used in the calibration of the safety factors included in DNV-RP-F101, and presented in Table 2-2. For details see ref. /16 and 17/.

Variable	Distribution	Mean	Uncertainty
P_{INT}	Gumbel	1.05 MAOP	CoV= 3.0%
D	Deterministic	Actual	-
t	Normal	Nominal	CoV =3.0%
σ_u	Normal	1.09 SMTS	CoV = 3.0% and 6.0%
L_{meas}	Normal	Measured value	Specified
d/t	Normal	Measured value	Specified
X_M	Normal	1.05	StD = 10%
CoV is normalised standard deviation (CoV = StD/mean)			

The significance of each parameter varies, and some may be used as a fixed value, rather than a variable with associated distribution. However, the distributions (uncertainties) in the model and the sizing accuracy have to be included in a probabilistic assessment, where it is often seen that only one of these are accounted for. The model uncertainty X_M for the DNV-RP-F101 capacity equation is given in the Table 2-2, while the uncertainty in the sizing accuracy is given in Sec.3 of this RP.

In addition to the inspection accuracy, the corrosion rate will also add to the uncertainty of the future defect size.

3. Calibrated safety factor (Part A)

3.1 Introduction

The approach given in Part A includes calibrated safety fac-

tors. 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.

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.

3.2 Reliability levels

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

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

Subsea 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 injection pipelines. For more details see ref /8/ and other relevant onshore and offshore pipeline codes.

3.3 Partial safety factors and fractile values

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

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

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

The safety factors are determined based on:

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

Safety factor γ_m is given in Table 3-2 for inspection results based on relative depth measurements, (e.g. Magnetic Flux Leakage (MFL) intelligent pig measurements), and for absolute depth measurements (e.g. Ultrasonic Wall Thickness or Wall Loss Measurements). MFL is a relative measurement where the defect depth measurement and the accuracy are given as a fraction of the wall thickness. The UT is an absolute measurement where the local wall thickness, the defect depth

measurement and the accuracy are given directly.

Inspection method	Safety Class		
	Low	Normal	High
Relative (e.g. MFL)	$\gamma_m = 0.79$	$\gamma_m = 0.74$	$\gamma_m = 0.70$
Absolute (e.g. UT)	$\gamma_m = 0.82$	$\gamma_m = 0.77$	$\gamma_m = 0.72$

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

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

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

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

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

- $StD[d/t]$ = $acc_rel / NORMSINV(0.5 + conf/2)$
- acc_rel = the relative depth accuracy, e.g. 0.2 (0.2 t)
- $conf$ = the confidence level, e.g. 0.8 (80%)
- $NORMSINV$ = a Microsoft Excel function. $NORMSINV(x)$ returns the inverse of the standard normal cumulative distribution at probability x.

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

Relative sizing accuracy	Confidence level	
	80% (0.80)	90% (0.90)
Exact \pm (0.0 of t)	$StD[d/t] = 0.00$	$StD[d/t] = 0.00$
\pm 0.05 of t	$StD[d/t] = 0.04$	$StD[d/t] = 0.03$
\pm 0.10 of t	$StD[d/t] = 0.08$	$StD[d/t] = 0.06$
\pm 0.20 of t	$StD[d/t] = 0.16$	$StD[d/t] = 0.12$

Fig.3-1 illustrates a sizing accuracy of $\pm 5\%$ of t, quoted with a confidence level of 80%. A Normal distribution is assumed.

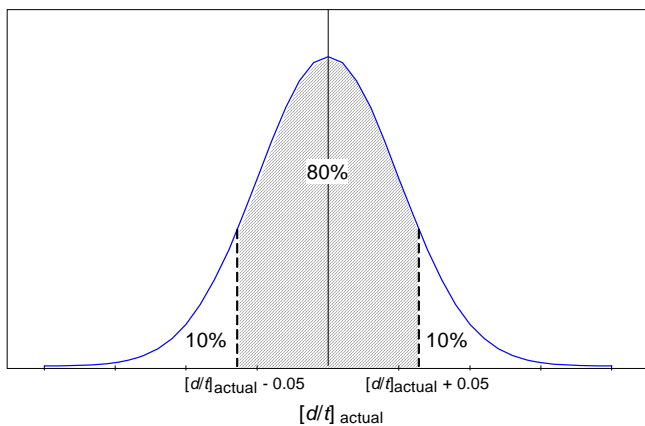


Figure 3-1
Example of a sizing accuracy of $\pm 5\%$ of t, quoted with a confidence level of 80%

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

- $StD[d/t]$ = $\sqrt{2} acc_abs / (t \cdot NORMSINV(0.5 + conf/2))$
- acc_abs = the absolute depth accuracy, e.g. 0.5 (0.5 mm)
- $conf$ = the confidence level, e.g. 0.8 (80%)
- $NORMSINV$ = a Microsoft Excel function.

Note that the expression is dependent on the wall thickness.

This function is a slightly conservative approximation of the detailed expressions of the standard deviations, see Appendix C, of absolute measurements used in the 1999 version of this RP. The detailed expressions may also be used. The simplification conservatively assumes $d = t$ in the calculation of $StD[d/t]$.

A selected set of calculated standard deviations for absolute sizing accuracy is given in Table 3-4 through Table 3-6 for a wall thickness of 6.35 mm, 12.7 mm and 19.05 mm.

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

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

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

Safety factor γ_d and fractile value ϵ_d :

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

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	$\gamma_d = 1.20$	$\gamma_d = 1.38$	$\gamma_d = 1.58$

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

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

Table 3-8 Polynomial Equations for Partial Safety Factor and Fractile Value, see Table 3-7

Safety Class	γ_d and ε_d	Range
Low	$\gamma_d = 1.0 + 4.0 a$	$a < 0.04$
	$\gamma_d = 1 + 5.5 a - 37.5 a^2$	$0.04 \leq a < 0.08$
	$\gamma_d = 1.2$	$0.08 \leq a \leq 0.16$
Normal	$\gamma_d = 1 + 4.6 a - 13.9 a^2$	$a \leq 0.16$
High	$\gamma_d = 1 + 4.3 a - 4.1 a^2$	$a \leq 0.16$
(all)	$\varepsilon_d = 0$	$a \leq 0.04$
	$\varepsilon_d = -1.33 + 37.5 a - 104.2 a^2$	$0.04 < a \leq 0.16$

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

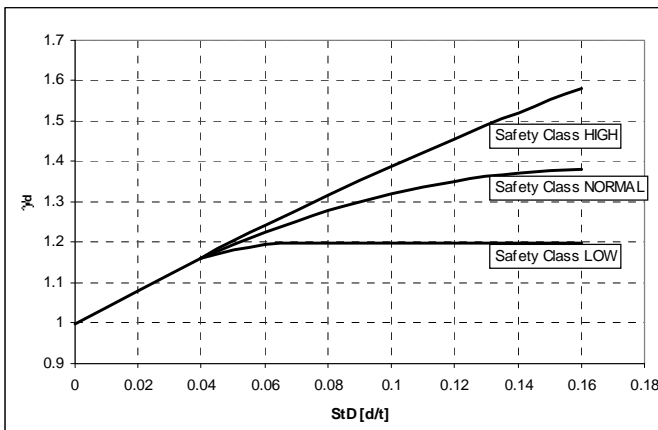


Figure 3-2
Partial safety factor γ_d with $StD[d/t]$.

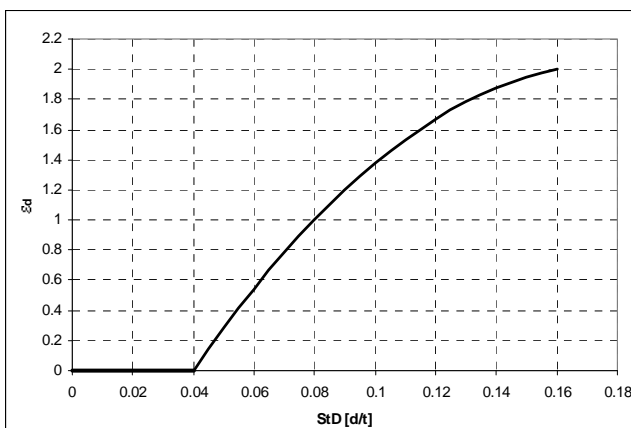


Figure 3-3
Safety factor ε_d with $StD[d/t]$.

3.4 Circumferential corrosion

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

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

Safety Class	Factor γ_{mc}	Factor η
Low	$\gamma_{mc} = 0.81$	$\eta = 0.96$
Normal	$\gamma_{mc} = 0.76$	$\eta = 0.87$
High	$\gamma_{mc} = 0.71$	$\eta = 0.77$

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

3.5 Usage factors for longitudinal stress

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

Table 3-10 Usage factors ξ

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

3.6 System effect

The target reliability levels are for a single metal loss defect. If the defect in question is clearly the most severe defect governing the allowable corroded pipe pressure, then this defect will also govern the reliability level of the pipeline for failure due to corrosion. In the case of several corrosion defects each with approximately the same 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.

3.7 Supplementary material requirements

The safety factors in Table 3-11 and Table 3-12 can be used if the material requirements are documented with increased confidence for the yield and ultimate strength as given in e.g. DNV-OS-F101 additional material requirement U, or equivalent.

The safety factors in Table 3-11 and Table 3-12 may only be used if it is explicitly documented that the supplementary material requirements are fulfilled.

Table 3-11 Partial safety factor γ_m for pipelines with supplementary material requirements

Inspection method	Safety Class		
	Low	Normal	High
Relative (e.g. MFL)	$\gamma_m = 0.82$	$\gamma_m = 0.77$	$\gamma_m = 0.73$
Absolute (e.g. UT)	$\gamma_m = 0.85$	$\gamma_m = 0.80$	$\gamma_m = 0.75$

Table 3-12 Partial safety factors γ_{mc} and η for pipelines with supplementary material requirements

Safety Class	Factor γ_{mc}	Factor η
Low	$\gamma_{mc} = 0.85$	$\eta = 1.00$
Normal	$\gamma_{mc} = 0.80$	$\eta = 0.90$
High	$\gamma_{mc} = 0.75$	$\eta = 0.80$

4. Assessment of a Single Defect (Part A)

4.1 Requirements

Isolated metal loss defects are to be individually assessed as single defects, see Fig.4-1.

Adjacent defects can interact to produce a failure pressure that is lower than the individual failure pressures of the isolated defects treated as single defects. For the case where interaction occurs, the single defect equation is no longer valid and the procedure given in Sec.5 must be applied. Fig.4-2 shows the key dimensions for defect interaction.

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

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

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

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

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

4.2 Longitudinal corrosion defect, internal pressure loading only

4.2.1 Acceptance equation

The allowable corroded pipe pressure of a single metal loss defect subject to internal pressure loading is given by the following acceptance equation. The acceptance equation has not been validated for defects dimensions where the breadth (circumferential extent) of the defect exceeding the length of the defect.

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

where:

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

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

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

p_{corr} is not allowed to exceed p_{mao} . The static head and pressure reference height should be accounted for.

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

4.2.2 Alternative applications

The form of the acceptance equation is made to determine the acceptable operating pressure for a measured corrosion defect in a pipeline. The equation can be re-arranged to determine the acceptable measured defect size for a specified operational pressure.

By setting the specified operating pressure p_{oper} equal to p_{corr} , the equation can be re-arranged to calculate maximum acceptable measured defect depths:

$$(d/t)_{meas,acc} = \frac{1}{\gamma_d} \frac{(1 - p_{oper} / p_0)}{\left(1 - \frac{p_{oper} / p_0}{Q}\right)} - \varepsilon_d \cdot \text{StD}[d/t]$$

where

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

(The limitations in the equation are not explicitly given)

4.2.3 Maximum acceptable defect depth

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

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

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

The RP includes two requirements for maximum acceptable defect depth:

- a) Measured defect depth shall not exceed 85% of the wall thickness, i.e. minimum remaining wall thickness $\geq 15\%$ of the (nominal) wall thickness.
- b) The measured defect depth plus the uncertainty in the defect sizing can not exceed the wall thickness, with the reliability level applicable for the defect, identified by the safety or location class.

The maximum acceptable measured defect depths are dependent on the inspection method, sizing capabilities and safety or location class. Selected examples are given in Table 4-1.

Safety Class	Inspection method	Accuracy	Conf. level	Max acceptable measured depth
Normal	MFL	+/- 5%	80%	0.86 t ¹⁾
Normal	MFL	+/- 10%	80%	0.70 t
High	MFL	+/- 10%	80%	0.68 t
Normal	MFL	+/- 20%	80%	0.41 t

¹⁾ Limited to maximum 0.85 t, see a) above.

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

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

This method is only valid for single defects.

The development of the method is outlined in ref. /17/.

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 pro-

cedure:

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:

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

where:

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

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

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

4.4 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:

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

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 ηf_y , in tension or in compression. The longitudinal pipe wall stress shall include the effect of all loads, including the pressure.

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

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

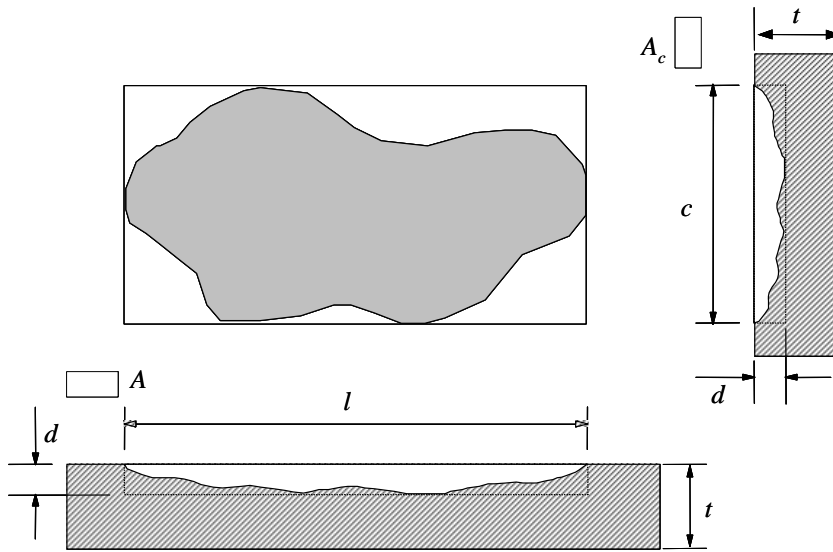


Figure 4-1
 Single defect dimensions

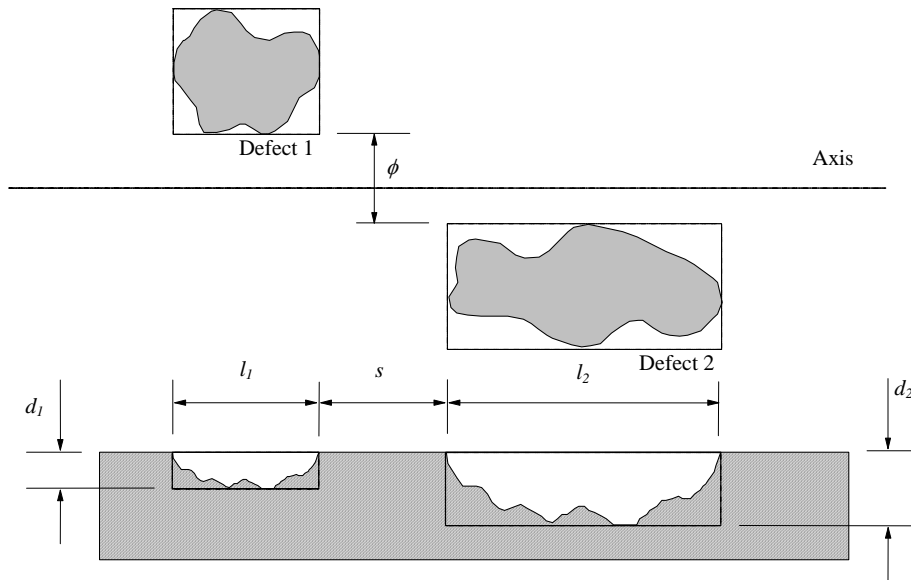


Figure 4-2
 Interacting defect dimensions

5. Assessment of Interacting Defects (Part A)

5.1 Requirements

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

- The angular position of each defect around circumference of the pipe.

- The axial spacing between adjacent defects.
- Whether the defects are internal or external.
- The length of each individual defect.
- The depth of each individual defect.
- The width of each individual defect.

5.2 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---of---G-u-i-d-a-n-c-e---n-o-t-e---

STEP 1 For regions where there is background metal loss (less than 10% of the wall thickness) the local pipe wall thickness and defect depths can be used (see Fig.5-1).

STEP 2 The corroded section of the pipeline should be divided into sections of a minimum length of $5.0\sqrt{Dt}$, with a minimum overlap of $2.5\sqrt{Dt}$.

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

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

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

STEP 4 Consider each projection line in turn. If defects lie within $\pm Z$, they should be projected onto the current projection line (see Fig.5-2).

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 Fig.5-3). 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 Fig.5-4).

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:

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

where:

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

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

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---of---G-u-i-d-a-n-c-e---n-o-t-e---

STEP 7 Calculate the combined length of all combinations of adjacent defects (see Fig.5-5 and Fig.5-6). 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 Fig.5-5):

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

STEP 9 Calculate the allowable corroded pipe pressure of the combined defect from n to m (p_{nm}) (see Fig.5-6, using l_{nm} and d_{nm} in the single defect equation:

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

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:

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

Guidance note:

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

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

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.

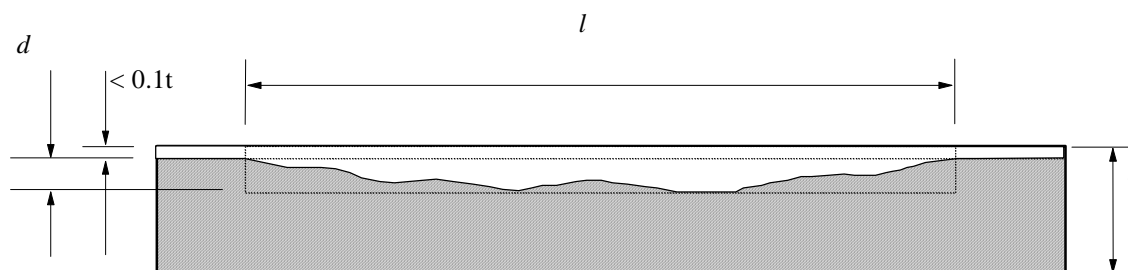


Figure 5-1
Corrosion depth adjustment for defects with background corrosion

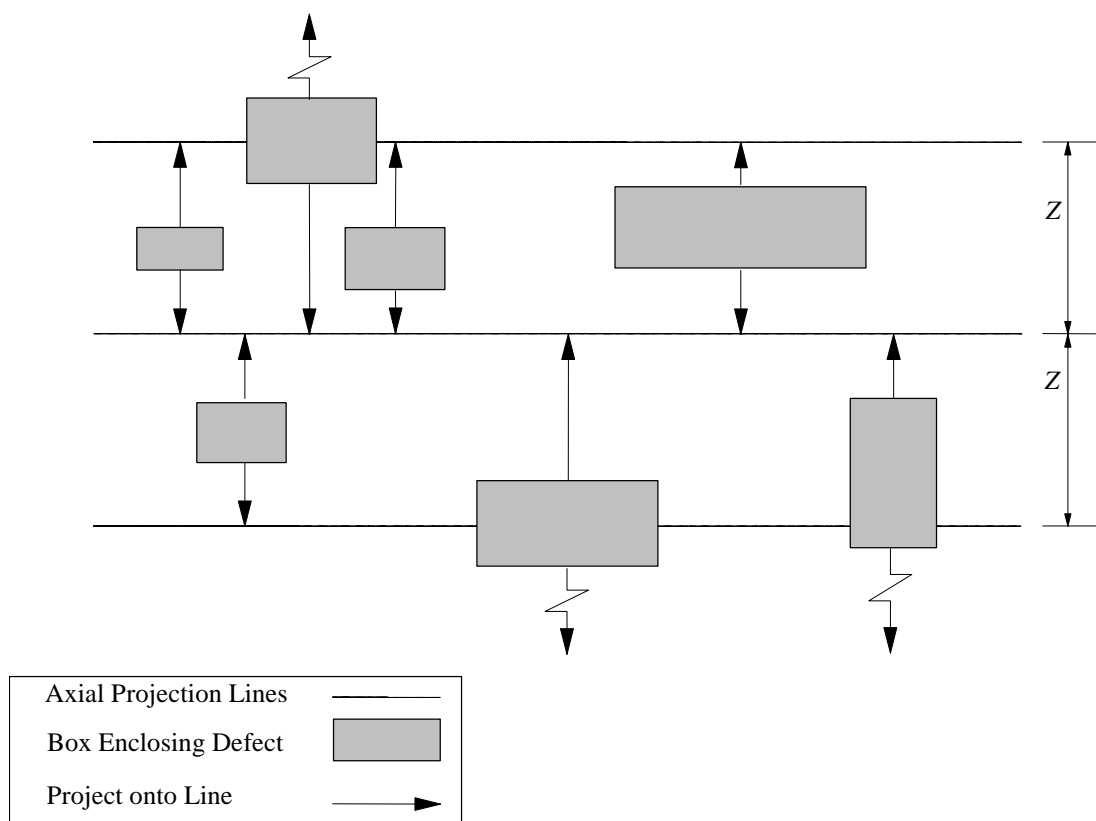


Figure 5-2
Projection of circumferentially interacting defects

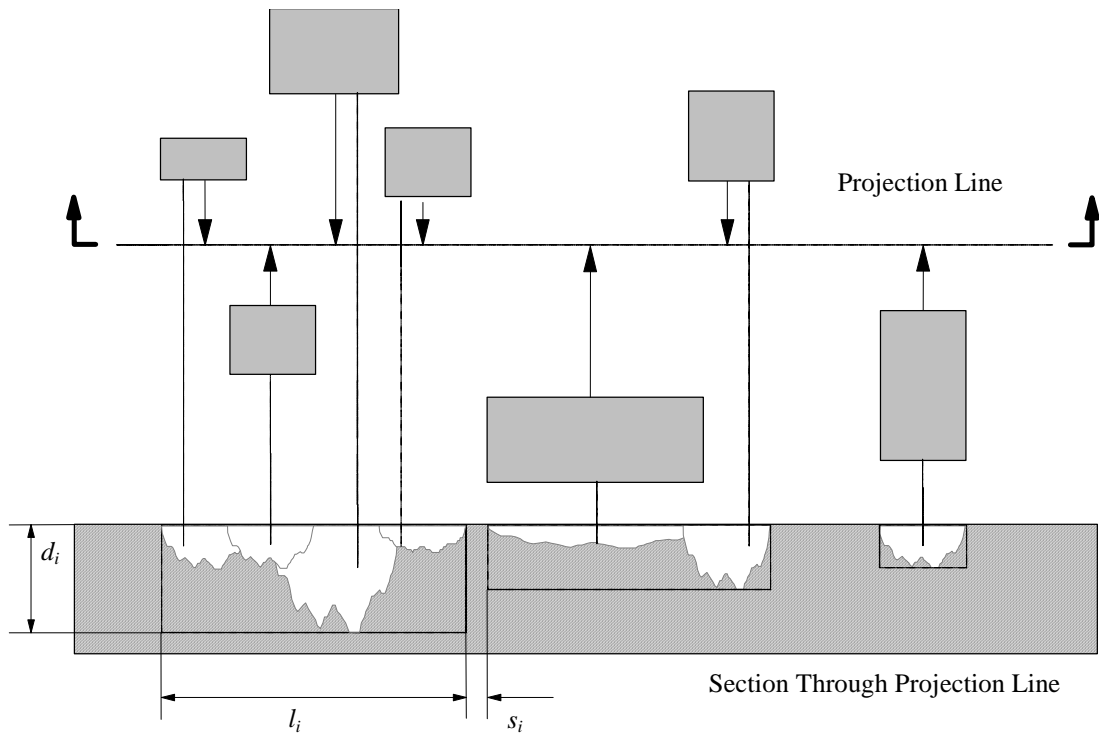


Figure 5-3
Projection of overlapping sites onto a single projection line and the formation of a composite defect

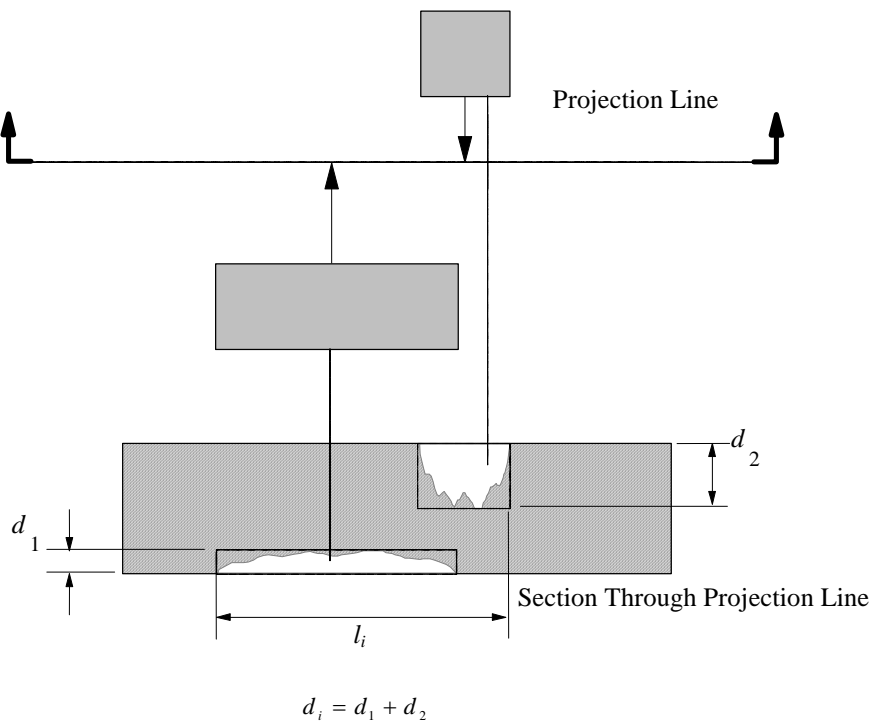
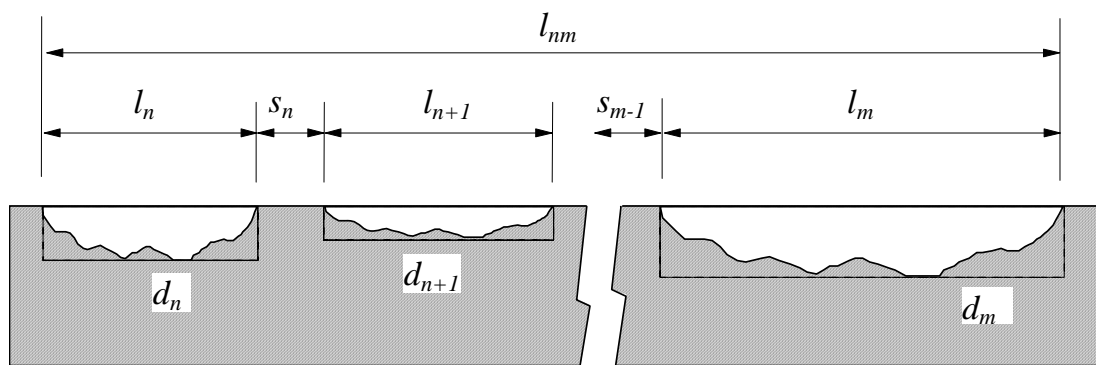


Figure 5-4
Projection of overlapping internal and external defects onto a single projection line and the formation of a composite defect



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

Figure 5-5
Combining interacting defects

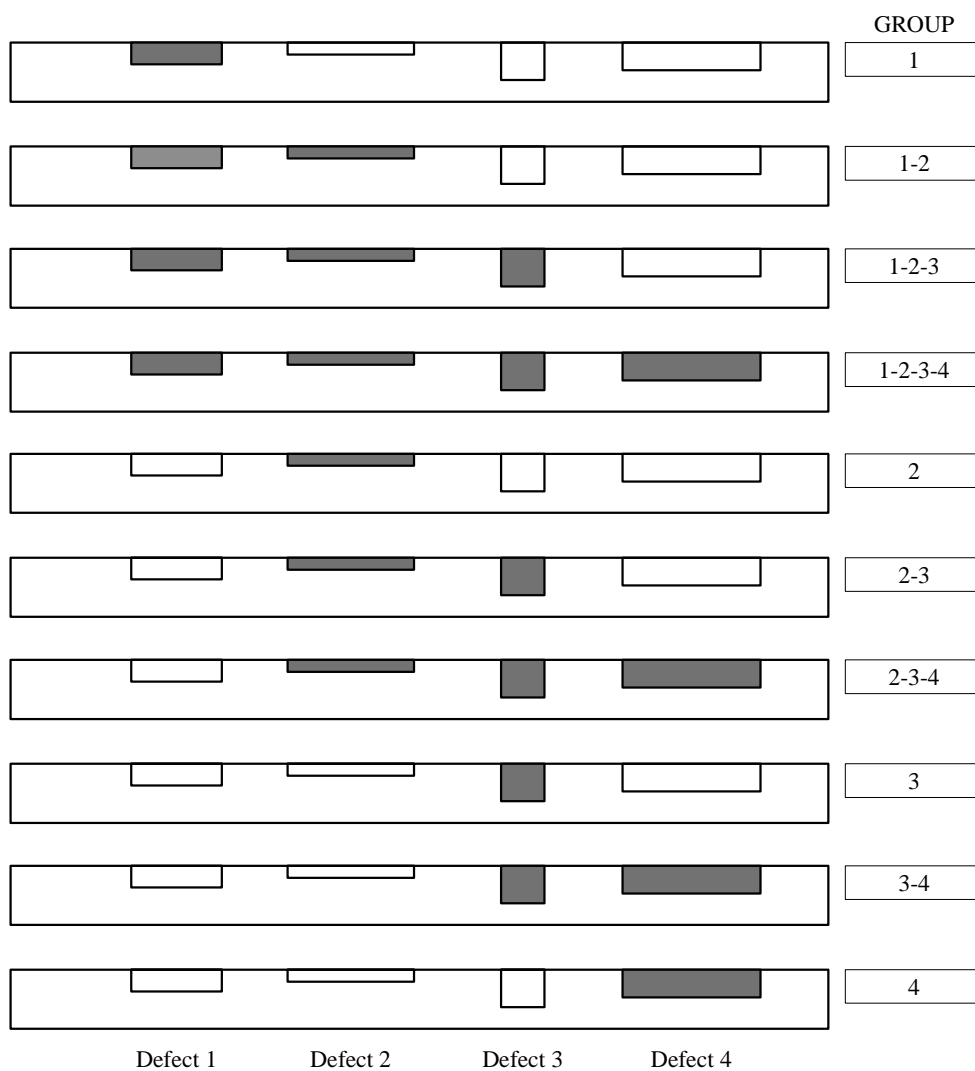


Figure 5-6
Example of the grouping of adjacent defects for interaction to find the grouping that gives the lowest estimated failure pressure

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 Fig.6-1 and Fig.6-2. 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 Sec.5).

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---of---G-u-i-d-a-n-c-e---n-o-t-e---

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

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

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

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

where:

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

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

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

Fully correlated depth measurements:

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

Guidance note:

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

6. Assessment of Complex Shaped Defects (Part A)

6.1 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.

6.2 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.

correlated depth measurements.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

STEP 3 Divide the maximum defect depth into increments, and perform the below calculations for all depth increments (d_j) (see Fig.6-1). 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 Fig.6-2). The recommended number of increments is between 10 and 50.

STEP 4 Calculate the average depth of an idealised ‘patch’ as follows (see Fig.6-2):

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

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:

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

Calculate also for use in Step 7:

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

where:

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

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

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

Fully correlated depth measurements:

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

Guidance note:

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

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

STEP 6 For each of the idealised ‘pits’, calculate the area loss in the nominal thickness cylinder, as shown in Fig.6-2, 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 Fig.6-1).

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

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:

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

where:

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

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

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} .

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

STEP 10 Calculate the combined length of all combinations of adjacent defects (see Fig.5-5 and Fig.5-6). 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 Fig.5-5):

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

STEP 12 Calculate the allowable corroded pipe pressure of the combined defect from n to m (p_{nm}) (see Fig.5-6), using l_{nm} , t_e and $d_{e,nm}$ in the single defect equation:

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

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:

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

Guidance note:

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

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

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

STEP 15 Calculate the allowable pipe pressure according to the single defect equation in Sec.4.2 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} .

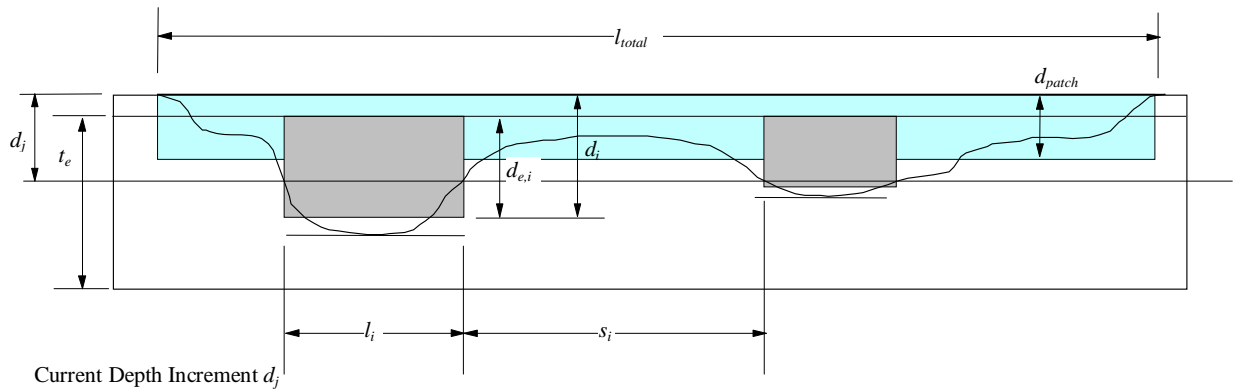


Figure 6-1 Subdivision of complex shape into idealised 'patch' and 'pits'

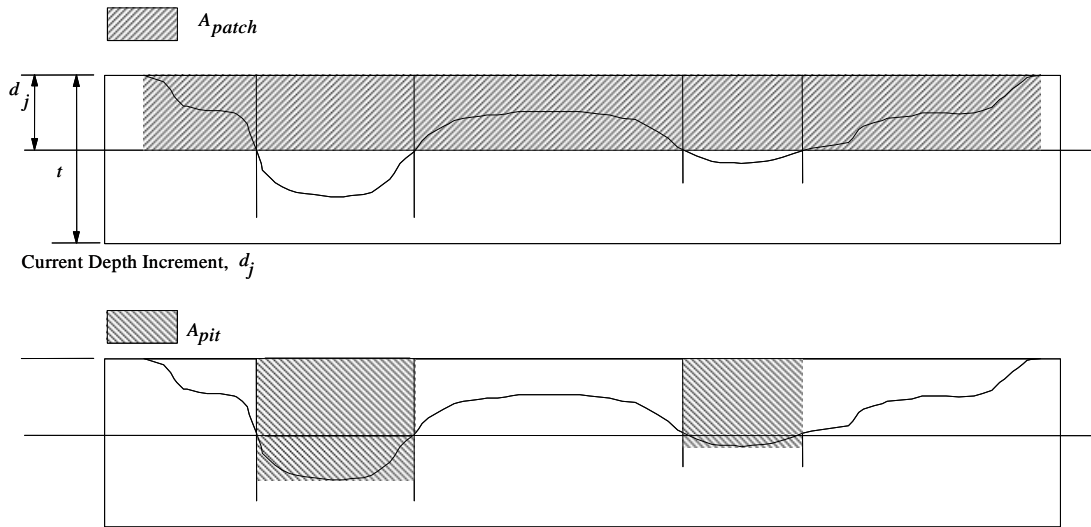


Figure 6-2
Definition of A_{patch} and A_{pit} for subdivision of complex shape into idealised 'patch' and 'pits'

7. Allowable Stress Approach (Part B)

7.1 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.

7.2 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 = *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:

$$F = F_1 F_2$$

8. Assessment of a Single Defect (Part B)

8.1 Requirements

Isolated metal loss defects are to be individually assessed as single defects, see Fig.4-1.

Adjacent defects can interact to produce a failure pressure that is lower than the individual failure pressures of the isolated defects treated as single defects. For the case where interaction occurs, the single defect equation is no longer valid and the procedure given in Sec.9 must be applied. Fig.4-2 shows the key dimensions for defect interaction.

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

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

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

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

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

8.2 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):

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

where:

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

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

$$P_{sw} = F P_f$$

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

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

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

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

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

Method for assessing a single defect subject to tensile longitudinal and/or bending stresses is given in e.g. refs /6/ and /12/

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 Fig.8-1).

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

$$\sigma_L > \sigma_1$$

where:

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

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

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

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

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 (Fig.8-2):

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

where:

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

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

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

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

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

$$P_{sw} = F P_f$$

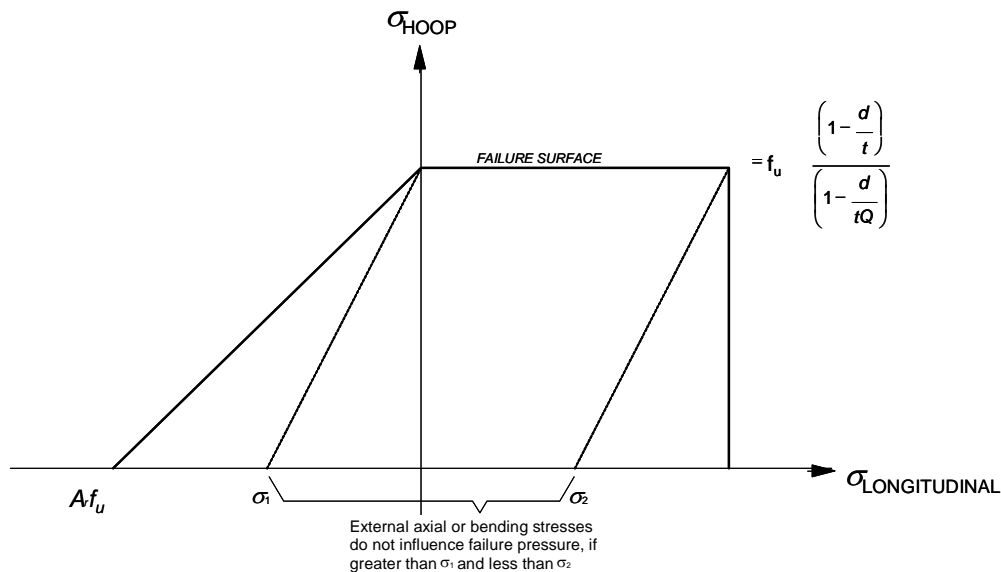


Figure 8-1
 Range of superimposed longitudinal and/or bending loads that will not influence the failure pressure

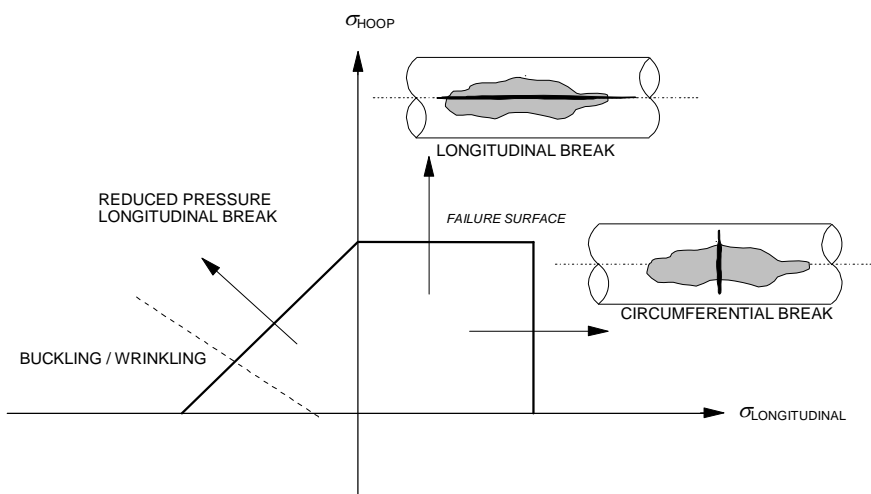


Figure 8-2
 Influence of applied loads on the failure mode of a corrosion defect

9. Assessment of Interacting Defects (Part B)

9.1 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 Sec.8 for assessing corrosion defects under combined loads are only valid for single defects.

The minimum information required comprises:

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

9.2 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).

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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 Fig.5-1).

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

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

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

STEP 4 Consider each projection line in turn. If defects lie within $\pm Z$, they should be projected onto the current projection line (see Fig.5-2).

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 Fig.5-3). 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 Fig.5-4).

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:

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

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} .

STEP 7 Calculate the combined length of all combinations of adjacent defects (see Fig.5-5 and Fig.5-6). 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 Fig.5-5):

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

STEP 9 Calculate the failure pressure of the combined defect from n to m (P_{nm}) (see Fig.5-6), using l_{nm} and d_{nm} in the single defect equation:

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

where:

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

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

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

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.

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

10.1 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.

10.2 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 analysis 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 Fig.6-1 and Fig.6-2. 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 Sec.9).

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---of---G-u-i-d-a-n-c-e---n-o-t-e---

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

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

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

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

where:

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

STEP 3 Divide the maximum defect depth into increments, and perform the below calculations for all depth increments (d_j) (see Fig.6-1). 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 Fig.6-2). The recommended number of increments is between 10 and 50.

STEP 4 Calculate the average depth of an idealised 'patch' as follows (see Fig.6-2):

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

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

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

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 Fig.6-2, 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_{patch}), as calculated in Step 5 (see Fig.6-1).

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

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:

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

where:

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

Guidance note:

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

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

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:

$$P_{sw} = F P_f$$

STEP 10 Calculate the combined length of all combinations of adjacent defects (see Fig.5-5 and Fig.5-6). 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 Fig.5-5):

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

STEP 12 Calculate the failure pressure of the combined defect from n to m (P_{nm}) (see Fig.5-6), using l_{nm} , t_e and $d_{e, nm}$ in the single defect equation:

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

where:

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

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

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

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

STEP 15 Calculate the failure pressure according to the single defect equation in Sec.8.2, Step 1, using the maximum defect depth and the total length of the defect.

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APPENDIX A EXAMPLES FOR PART A

A.1 Single defect assessment

Example 1

This example is for the assessment of an isolated corrosion defect under internal pressure loading (see Sec.4.2), 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 ±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.

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

(alt. calc: StD[d/t] = acc_rel / NORMSINV(0.5+conf/2) = 0.1 / NORMSINV(0.5 + 0.8/2) = 0.0780)

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

$$\begin{aligned}\gamma_m &= 0.74 \\ \gamma_d &= 1.28 \\ \epsilon_d &= 1.0\end{aligned}$$

Using the procedure for assessing single defects given in Sec.4.2.

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

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

$$f_u = \text{SMTS}$$

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

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.

Example 2

This example is for the assessment of an isolated corrosion defect under internal pressure loading (see Sec.4.2), 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 (~ 25%)

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 ±1.0mm 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.

Calculation of standard deviation (this example is also included in Table 3-6):

$$\begin{aligned}\text{StD}[d/t] &= \sqrt{2} \text{acc_abs} / (t \cdot \text{NORMSINV}(0.5 + \text{conf}/2)) \\ &= \sqrt{2} \cdot 1.0 / (19.1 \cdot \text{NORMSINV}(0.5 + 0.8/2)) = 0.058\end{aligned}$$

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

Taking the partial safety factors from Table 3-8

$$\gamma_d = 1 + 4.6 \text{StD}[d/t] - 13.9 \text{StD}[d/t]^2 = 1.22$$

$$\epsilon_d = -1.33 + 37.5 \text{StD}[d/t] - 104.2 \text{StD}[d/t]^2 = 0.49$$

Using the procedure for assessing single defects given in Sec.4.2 .

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

$$(d/t)^* = 0.25 + 0.49 \times 0.058 = 0.2546$$

$$p_{corr} = 0.77 \frac{2t \text{SMTS}}{(D-t)} \frac{(1 - 1.17(d/t)^*)}{\left(1 - \frac{1.17(d/t)^*}{Q}\right)} = 17.40 \text{ N/mm}^2$$

The allowable corroded pipe pressure is 17.40 N/mm² (174.0 bar). Therefore, the corrosion defect is acceptable, at the current time, for the maximum allowable operating pressure of 150 bar.

Example 3

This example is for the assessment of an isolated longitudinal corrosion defect under internal pressure loading and superimposed longitudinal compressive stresses (see Sec.4.3).

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 $\pm 10\%$ 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 3-3 (assuming that the sizing accuracy follows a Normal distribution).

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

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

$$\gamma_m = 0.74$$

$$\gamma_d = 1.28$$

$$\varepsilon_d = 1.0$$

$$\xi = 0.85$$

Using the procedure for assessing single defects given in Sec.4.2.

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

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

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

Where $f_u = SMTS$

Using the procedure given in Sec.4.3.

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 (39.3bar). 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.

A.2 Interacting defects

Example 4

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

The basic properties required by the assessment are:

Outside Diameter	=	812.8 mm
Original Wall Thickness	=	20.1 mm
SMTS	=	530.9 N/mm ² (X65)

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 High.

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

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

Taking the partial safety factors from Tables 3-2 and 3-7

$$\gamma_m = 0.70$$

$$\gamma_d = 1.32$$

$$\varepsilon_d = 1.0$$

Using the procedure for assessing interacting defects given in Sec.5:

The defects should be grouped into axial projections as described in Steps 1 to 5 of Sec.5.2.

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 (Sec.9) gives:

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

Assuming that the defect depth measurements are fully correlated:

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

Taking the partial safety factors from Tables 3-2 and 3-7

$$\gamma_m = 0.70$$

$$\gamma_d = 1.25$$

$$\varepsilon_d = 0.60$$

Allowable corroded pipe pressure (Step 9) = 15.40 N/mm²

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 15.40 N/mm² (154.0 bar).

A.3 Complex shaped defect

Example 5

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

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

As single defect:

Using the procedure for assessing single defects given in Sec.4, with a total length of 289 mm and maximum depth of 2.8 mm.

Calculation of standard deviation:

$$\text{StD}[d/t] = \sqrt{2} \text{acc_abs} / (t \cdot \text{NORMSINV}(0.5 + \text{conf}/2))$$

$$= \sqrt{2} \cdot 1.0 / 8.2 \cdot \text{NORMSINV}(0.5 + 0.9/2) = 0.0105$$

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

Taking the partial safety factor from Table 3-2.

$$\gamma_m = 0.77$$

Taking the partial safety factors from Table 3-8.

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

$$\varepsilon_d = 0.0$$

Allowable Corroded Pipe Pressure = 8.12 N/mm²

When the complex shaped defect is assessed as a single defect, using the total length and maximum depth, then the allowable corroded pipe pressure is 8.12 N/mm².

As single defect with average depth:

Using the procedure for assessing complex shaped defects given in Sec.6:

Single Defect Solution (Steps 1 to 2)

Step 1 is to calculate the average depth of the defect from the projected total area loss of the defect. The total projected metal loss area is calculated to be 421.94 mm², resulting in an average depth of 1.46mm for the length of 289 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:

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

Safety factors as above.

Allowable Corroded Pipe Pressure = 9.52 N/mm²

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. Fig.A-2 shows the variation of the allowable corroded pipe pressure estimate with depth. The minimum allowable corroded pipe pressure estimate was 9.19 N/mm² (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 Fig.A-1. 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 Fig.A-2.

Assuming that the defect depth measurements are fully correlated:

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

Safety factors as above

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.

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:

Minimum allowable corroded pipe pressure (Step 13) = 9.17 N/mm².

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 8.12 N/mm² (81.2 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 Fig.A-2), but not less than the pressure from Step 15.

Analysis of the defect as a complex profile, using the progressive depth method, gives an allowable corroded pipe pressure

estimate of 9.17 N/mm².

The allowable corroded pipe pressure is 9.17 N/mm² (91.7 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.

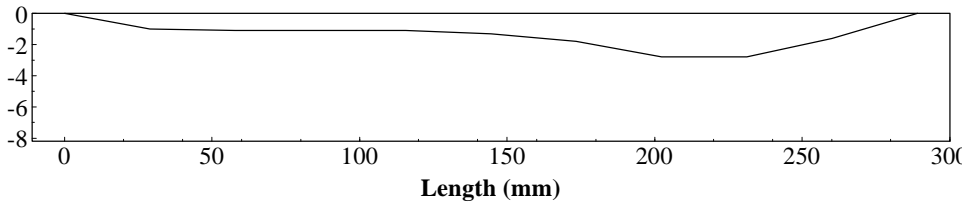


Figure A-1
Profile for actual corrosion defect - example assessment

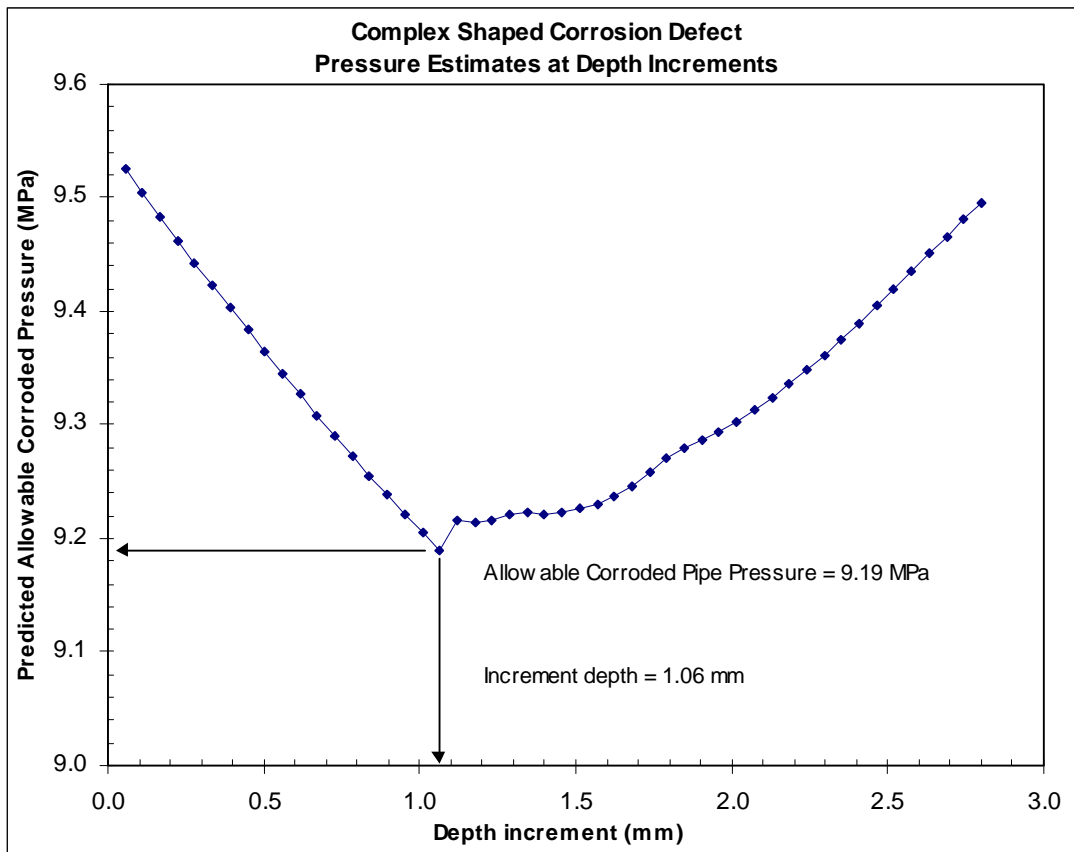


Figure A-2
Variations of the estimated failure pressure for actual corrosion defect - Example assessment

APPENDIX B EXAMPLES FOR PART B

B.1 Single defect assessment

B.1.1 Example 6

This example is for the assessment of an isolated corrosion defect under internal pressure loading only (see Sec.8.2).

The dimensions and material properties are summarised as follows:

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

Using the procedure for assessing single defects given in Sec.8.2.

Step 1 - Calculate the failure pressure using:

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

$f_u = \text{SMTS}$

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

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

The safe working pressure:

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

(This compares with a burst pressure of 20.50 N/mm² from a full scale test, with measured ultimate tensile strength of 608 MPa. Using the ultimate tensile strength and the capacity equation including the 1.05 factor this will result in a capacity prediction of 19.1 N/mm², a deviation of about 7%).

B.1.2 Example 7

This example is for the assessment of an isolated corrosion defect under internal pressure and compressive longitudinal loading (see Sec.8.3).

The dimensions and material properties are summarised as follows:

Outside diameter	=	219.0 mm
Original wall thickness	=	14.5 mm
SMTS (= f_u)	=	455.1 N/mm ² (X52)
Defect length (max)	=	200.0 mm
Defect width (max)	=	100.0 mm
Defect depth (max)	=	62% of wall thickness

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

Using the procedure for assessing single defects given in Sec.8.3

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

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

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

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

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

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

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

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

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

$$Q = 2.2147$$

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

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

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

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

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.

B.2 Interacting defects

B.2.1 Example 8

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

The basic properties required by the assessment are:

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

Using the procedure for assessing interacting defects given in Sec.9:

The defects should be grouped into axial projections as described in Steps 1 to 5 of Sec.9.2.

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 (Sec.9) for the combined defect gives :

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

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

B.2.2 Example 9

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

The basic properties required by the assessment are:

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

Using the procedure for assessing interacting defects given in Sec.9:

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 (Sec.9)

gives:

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

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

B.3 Complex shaped defect

B.3.1 Example 10

This example is an analysis of the failure pressure of a complex shaped defect (see Sec.10). 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 Fig. B-1:

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

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

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

Using the procedure for assessing complex shaped defects given in Sec.10:

Single Defect Solution (Steps 1 to 2)

Total length = 572.0 mm
Maximum depth = 17.1 mm

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

Total projected area loss = 7584.6 mm²
Average depth = 13.26 mm

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

Failure pressure = 16.23 N/mm²

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 Fig.B-2.

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

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

Depth of increment no. 12 = 4.1 mm
Patch average area (Step 4) = 2347 mm²
Patch length = 572.0 mm
Patch average depth (Step 4) = 4.1 mm
Patch failure pressure (Step 5) = 27.47 N/mm²

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

Number of Pits = 1

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

Effective reduced thickness = 19.42 mm

Pit	Average Depth (mm) (Step 6)	Average Depth In Reduced Wall (mm) (Step 8)	Length (mm)	Failure Pressure (N/mm ²) (Step 9)
1	13.26	10.58	571.9	15.54

Pit interactions based on the reduced thickness pipe.

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

Minimum pressure = 15.54 N/mm²

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 Sec.8.2 .

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 Fig.B-4).

Analysis of the defect as a complex profile using the progressive depth method, without the application of a safety factor, gives a failure pressure estimate of 13.40 N/mm² from a section depth of 13.0 mm.

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

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

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

B.3.2 Example 11

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

The pipeline geometry and properties are summarised as follows:

Outside diameter = 611.0 mm
Wall thickness = 8.20 mm
SMTS = 571.0 N/mm²

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

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 Sec.10:

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. Fig.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 Fig.B-4. The effect of the relatively distinct change in profile at this depth produces a sharp change in the estimated failure pressure curve, as shown in Fig.B-4.

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

Step depth = 1.06 mm
Patch average area (*Step 4*) = 280.4 mm²
Patch length = 289.0 mm
Patch average depth (*Step 4*) = 0.97 mm
Patch failure pressure (*Step 5*) = 15.68 N/mm²
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 Fig.B-4).

Analysis of the defect as a complex profile using the progressive depth method, without the application of a safety factor, gives a failure pressure estimate of 13.21 N/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 Sec.8.

Total length = 289.0 mm
Maximum depth = 2.8 mm
Failure pressure = 11.86 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 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:

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

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

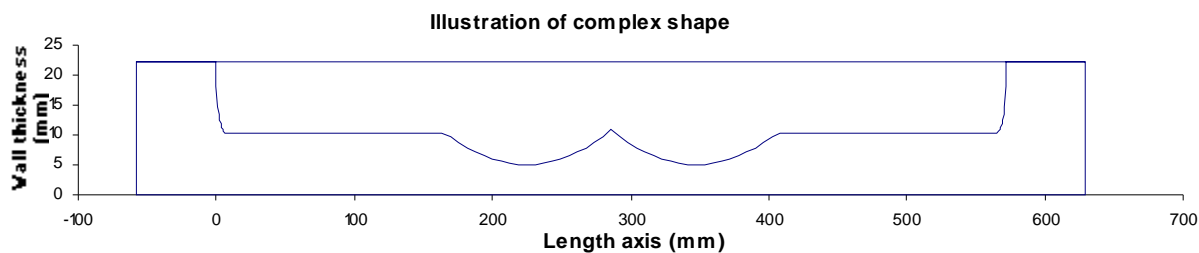


Figure B-1
Profile for complex shaped defect - Example assessment

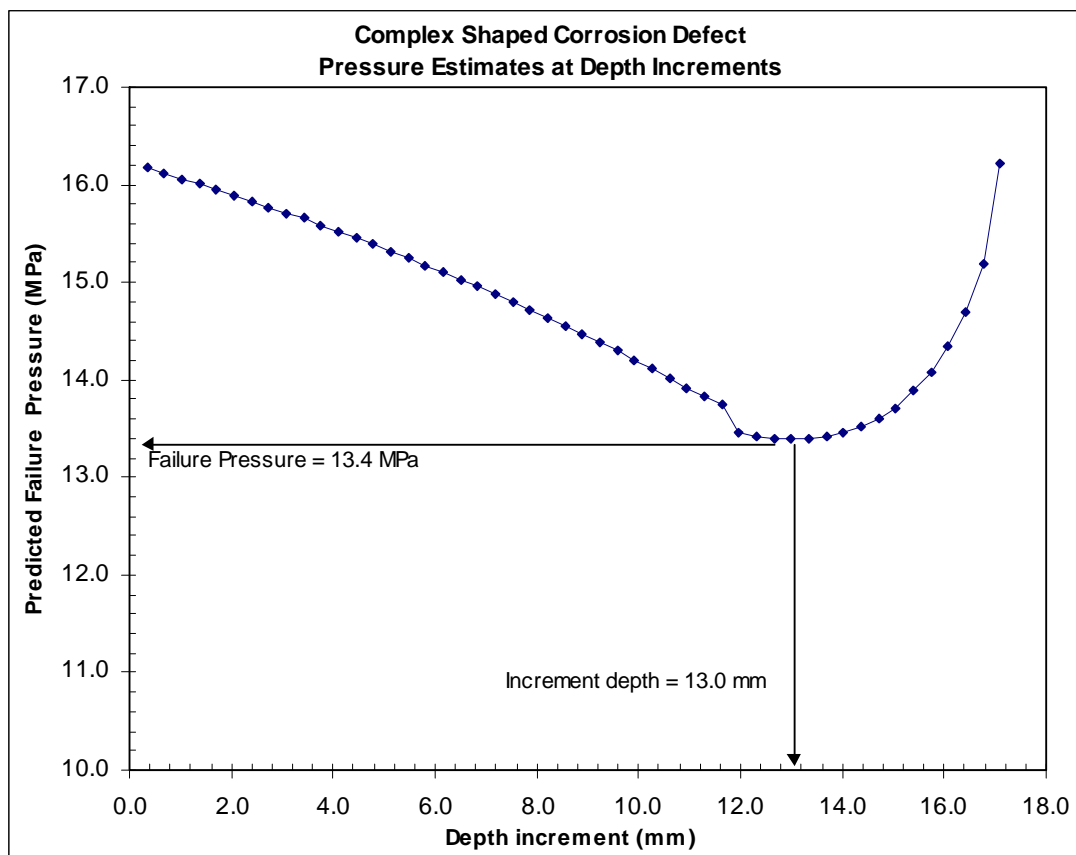


Figure B-2
Variations of the estimated failure pressure for complex shaped defect - Example assessment

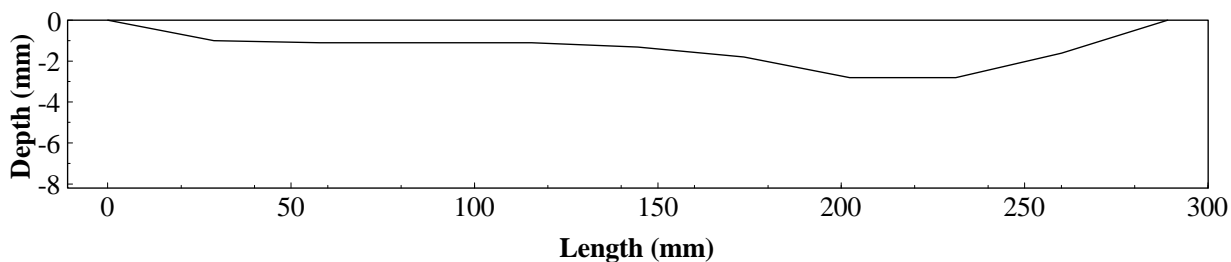


Figure B-3
Profile for actual corrosion defect - Example assessment

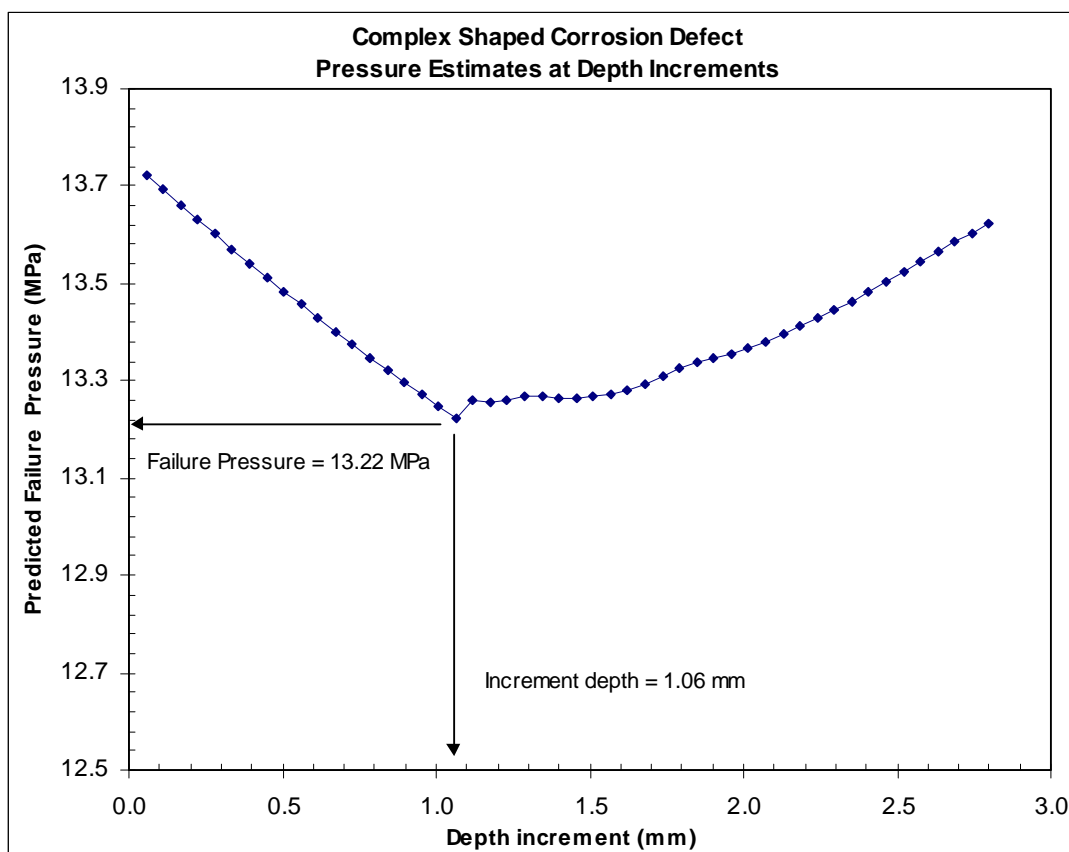


Figure B-4
Variations of the estimated failure pressure for actual corrosion defect - Example assessment

APPENDIX C

DETAILED CALCULATION OF MEASUREMENT ACCURACIES

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

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

The difference between fully correlated measurements and uncorrelated measurements can be explained from the following simple example: two adjacent pits of equal depth. Fully correlated measurements of the depth of two adjacent pits of equal depth would give the same value, because the measurement error would be 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 may give different values for each pit. If the same uncorrelated measurement technique was applied to many pits of the same depth, then the average value of the depth measurements would give an estimate of the actual depth of the pits.

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

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

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

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

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

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

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

where

$$Z_1 = \ln(r)$$

$$Z_2 = \ln(t).$$

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

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

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

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

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

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:

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

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

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

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

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

where

$$Z_1 = \ln(d)$$

$$Z_2 = \ln(t).$$

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

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

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

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

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

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

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

C.3 Application of absolute depth measurement

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

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

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

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

$$\text{StD}[l] \leq 20\text{StD}[r]$$

$$\text{StD}[t] \leq \text{StD}[r]$$

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, $\text{StD}[d/t]$, of the relative corrosion depth may be written as:

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

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

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

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

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

$$\text{StD}[l] \leq 20\text{StD}[d]$$

$$\text{StD}[t] \leq \text{StD}[d]$$

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

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

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

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

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