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UNIFIED GUIDANCE DOCUMENT

GUIDANCE FOR THE ASSESSMENT OF CORROSION IN LINEPIPE

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GUIDANCE FOR
THE ASSESSMENT OF CORROSION IN LINEPIPE

1. GENERAL

1.1. Introduction

This document provides guidance for assessing pipelines containing corrosion. Guidance is given for assessing corrosion defects subjected to:

i) Internal pressure loading only.
ii) Internal pressure loading combined with longitudinal compressive stresses.

This guidance document describes two alternative approaches to the assessment of corrosion, and is divided into two parts. The main difference between the two approaches is in their safety philosophy:

- The first approach, given in Part A, is in accordance to the safety philosophy adopted in the DNV Rules for Submarine Pipeline Systems (DNV'96)[1]. This part of the guidelines is a supplement to, and complies with, the DNV Rules for Submarine Pipeline Systems. Uncertainties associated with the sizing of the defect depth and the material properties, are specifically considered. Probabilistic calibrated equations (with partial safety factors) for the determination of the allowable operating pressure of a corroded pipeline are given.
- The second approach, given in Part B, is based on the ASD (Allowable Stress Design) format. The failure pressure (capacity) of the corrosion defect is calculated, and this failure pressure is multiplied by a single safety factor based on the original design factor. Consideration of the uncertainties associated with the sizing of the corrosion defect is left to the judgement of the user.

1.2. BG plc and DNV Research Projects

This document is a result of co-operation between BG Technology (part of BG plc) and DNV. The results from their respective joint industry projects have been merged, and form the technical basis of these guidelines.

The BG Technology project[2-6] 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[7-10] generated a database of 12 burst tests on pipes containing machined corrosion defects, that included the influence of superimposed loads on the failure pressure. A comprehensive database of 3D non-linear finite element analyses of pipes containing defects was also produced. Reliability methods were utilised for code calibration and the determination of partial safety factors.

1.3. Scope of Application

The methods provided in this document are intended to be used on corrosion damage in carbon steel pipelines that have been designed to recognised pipeline design code (including, but not limited to, the DNV Rules for Submarine Pipeline Systems (DNV'96), ASME B31.4, ASME B31.8, BS8010, IGE/TD/1, ISO/DIS 13623, CSA Z662-94)[1,11-16].

The implications of continuing defect growth are not covered by this guidance.

This guidance does not cover every situation that requires a fitness-for-purpose assessment and further methods may be required[17,18,19].

1.4. Applicable Defects

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

i) Internal corrosion in the base material.
ii) External corrosion in the base material.
iii) Corrosion in seam welds.
iv) Corrosion in girth welds.
v) Colonies of interacting corrosion defects.
vi) Metal loss due to grind repairs (provided that the grinding leaves a defect with a smooth profile, and that the complete 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.

1.5. Applied Loads

Internal pressure, and axial and/or bending loads may influence the failure of a corroded pipeline (see Figure 1).

The following combinations of loading are covered by the guidance given in this document:

	Partial Safety Factor Approach - Part A			**Allowable Stress Approach - Part B**		
	Internal pressure only	Internal pressure plus compressive longitudinal loads	Internal pressure plus tensile longitudinal and/or bending loads	Internal pressure only	Internal pressure plus compressive longitudinal loads	Internal pressure plus tensile longitudinal and/or bending loads
Single Defects	X	X	-	X	X	Appendix D
Interacting Defects	X	-	-	X	-	-
Complex Shaped Defects	X	-	-	X	-	-

The guidance given in this document is confined to the effects of internal pressure and compressive loading on longitudinal failure (see Figure 1), because the validation of these effects was specifically addressed in the DNV and BG Technology projects. The validation of the methods described in this document for the assessment of corrosion defects subject to internal pressure loading plus compressive longitudinal stresses (see Sections 3.3, 3.4 and 8.3), is not as comprehensive as the validation of the methods for the assessment of corrosion defects subject to internal pressure loading only.

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 guidance. Methods for assessing defects under combined internal pressure and bending loads and/or tensile longitudinal loads are recommended in other codes[e.g. References 18 and 19]. These methods have been included in Appendix D, in a format compatible with the rest of the guidance document, for those who wish to use these methods.

1.6. Exclusions

The following are outside the scope of this document:

i) Materials other than carbon linepipe steel.
ii) Linepipe grades in excess of X80[1].
iii) Cyclic loading.
iv) Sharp defects (i.e. cracks)[2].

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[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 17. , 18. and 19. .

v) Combined corrosion and cracking.
vi) Combined corrosion and mechanical damage.
vii) Metal loss defects attributable to mechanical damage (e.g. gouges)[3].
viii) Fabrication defects in welds.
ix) 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. The procedure is not recommended for applications where fracture is likely to occur. These may include[17]:

i) Materials manufactured prior to 1927 (i.e. prior to API/5L).
ii) Any material that has been shown to have a full scale initiation transition temperature above the operating temperature.
iii) Material of thickness greater than 12.7 mm, unless the full scale initiation transition temperature is below the operating temperature.
iv) Defects in mechanical joints, fabricated, forged, formed or cast fittings and attached appurtenances.
v) Defects in bond lines of flash welded (FW) or low frequency electric resistance welded (ERW) butt-welded pipe.
vi) Lap welded or furnace butt welded pipe.
vii) Semi-killed steels.

1.7. 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.

1.8. Assessment Procedure

A flow chart describing the assessment procedure (for both Part A and Part B) is shown in Figure 2.

1.9. Further Assessment

The intent of these guidelines is to provide simplified procedures for the assessment of corroded pipe. The results of the analysis should be conservative. If the corrosion defects are not found to be acceptable using the procedures given in these guidelines, then the user has the option of considering an alternative course of action to more accurately assess the remaining strength of the corroded pipeline. This could include, but is not limited to, detailed finite element analysis and/or full scale testing.

1.10. Worked Examples

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

1.11. Responsibility

Independent professional judgement must be exercised when using this guidance or the data presented herein. Anyone using this guidance must accept full responsibility for the consequences arising from such use.

1.12. Validation range

[HOLD]

1.13. Definitions

A ***Single Defect*** is one which does not interact with a neighbouring defect. The failure pressure of a single defect is independent of other defects in the pipeline.

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

An ***Interacting Defect*** is one which 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. Nomenclature and Abbreviations

[HOLD - Needs to be sorted logically]

A = Projected area of corrosion in the longitudinal plane through the wall thickness (mm^2).
A_{patch} = Area of an idealised 'patch' in a complex shaped defect (mm^2).
$A_{i,pit}$ = Area of the 'i'th idealised 'pit' in a complex shaped defect (mm^2).
d = Depth of corroded region (mm).
d_{ave} = Average depth of a complex shaped defect (mm).
= A/l_{total}
d_{ei} = The depth of the 'i'th idealised 'pit' in a pipe with an effectively reduced wall thickness due to a complex corrosion profile (mm).
$d_{e,nm}$ = 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).
d_i = Depth of an individual defect forming part of a colony of interacting defects (mm). Average depth of 'i'th idealised 'pit' in a progressive depth analysis of a complex shaped defect (mm).
d_j = The 'j'th depth increment in a progressive depth analysis of a complex shaped defect (mm).
d_{nm} = Average depth of a defect combined from adjacent defects n to m in a colony of interacting defects (mm).
d_{patch} = Average depth of an idealised 'patch' in a complex shaped defect (mm).
D = Nominal outside diameter (mm).
F = Total usage factor.
= F_1F_2
F_1 = Modelling factor.
F_2 = Operational usage factor.
i = Isolated defect number in a colony of N interacting defects.
j = Increment number in a progressive depth analysis of a complex shaped defect.
l = Longitudinal length of corroded region (mm).
l_i = Longitudinal length of an individual defect forming part of a colony of interacting defects (mm). Longitudinal length of 'i'th idealised 'pit' in a progressive depth analysis of a complex shaped defect (mm).
l_j = Longitudinal length increment in a progressive depth analysis of a complex shaped defect (mm).
l_{nm} = Total longitudinal length of a defect combined from adjacent defects n to m in a colony of interacting defects, including the spacing between them (mm).
l_{total} = Total longitudinal length of a complex shaped defect (mm).
N = Number of defects in a colony of interacting defects.
P_f = Failure pressure of the corroded pipe (N/mm^2).
P_{f_j} = Failure pressure for 'j'th depth increment in a progressive depth analysis of a complex shaped defect (N/mm^2).
P_{nm} = Failure pressure of combined adjacent defects n to m, formed from a colony of interacting defects (N/mm^2).
P_{patch} = Failure pressure of an idealised 'patch' in a complex shaped defect (N/mm^2).
P_{sw} = Safe working pressure of the corroded pipe (N/mm^2).
P_{total} = Failure pressure of a complex shaped defect when treated as a single defect (N/mm^2).
P_i = Failure pressures of individual defects forming a colony of interacting defects (N/mm^2).
Q = Length correction factor.
Q_i = Length correction factor of an individual defect forming part of a colony of interacting defects.
Q_{nm} = Length correction factor for a defect combined from adjacent defects n to m in a colony of interacting defects.
Q_{total} = Length correction factor for the total longitudinal length of a complex shaped defect (mm).

s = Longitudinal spacing between adjacent defects (mm).
s_i = Longitudinal spacing between adjacent defects forming part of a colony of interacting defects (mm).
t = Original, measured, pipe wall thickness, or pipe wall thickness as defined in the original design code (mm).
t_e = Equivalent pipe wall thickness used in a progressive depth analysis of a complex shaped defect (mm).
Z = Circumferential angular spacing between projection lines (degrees).
ϕ = Circumferential angular spacing between adjacent defects (degrees).

UTS = Ultimate tensile strength (N/mm^2).
YS = Yield strength (N/mm^2).
SMTS = Specified minimum tensile strength (N/mm^2).
SMYS = Specified minimum yield strength (N/mm^2).

YT = Yield to tensile ratio
= YS/UTS or SMYS/SMTS

c = Circumferential length of corroded region (mm).
θ = Ratio of circumferential length of corroded region to the nominal outside circumference of the pipe.
= $c/\pi D$
A_c = Projected area of corrosion in the circumferential plane through the wall thickness (mm^2).
A_r = Circumferential area reduction factor (one minus the ratio of projected area of corrosion in the circumferential plane through the wall thickness to the cross-sectional area of the pipe).
= $1\text{-}A_c/\pi Dt$
≈ $1\text{-}(d/t)\theta$
F_X = External applied longitudinal force (N).
M_X = External applied bending moment (Nmm).
σ_A = Longitudinal stress due to external applied axial force, based on the full wall thickness (N/mm^2).
σ_B = Longitudinal stress due to external applied bending moment, based on the full wall thickness (N/mm^2).
σ_L = Combined nominal longitudinal stress due to external applied loads (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).
K_1 = Factor to determine σ_2.
K_2 = Factor to determine σ_2.
Z = Factor to determine σ_2.
P_{comp} = Failure pressure of the corroded pipe for a single defect subject to internal pressure and compressive longitudinal stresses (N/mm^2).
$P_{tensile}$ = Failure pressure of the corroded pipe for a single defect subject to internal pressure and tensile longitudinal stresses (N/mm^2).
P_{press} = Failure pressure of the corroded pipe for a single defect subject to internal pressure only (N/mm^2).

γ_m = Partial safety factor for longitudinal corrosion model prediction.
γ_{mc} = Partial safety factor for circumferential corrosion model prediction.
γ_d = Partial safety factor for corrosion depth.
ε_d = Factor for defining a fractile value for the corrosion depth.
η = Partial safety factor for longitudinal stress for circumferential corrosion.
ξ = Usage factor for longitudinal stress.
N_m = Number of depth measurements taken to define the profile of a complex shaped defect.
r = remaining ligament thickness (mm).
E[X] = expected value of random variable X.
StD[X] = standard deviation of random variable X.

$\mathrm{CoV}[X]$ = coefficient of variation of random variable X.
= $\mathrm{StD}[X]/\mathrm{E}[X]$
$(X)^*$ = Characteristic value of X.

p_{mao} = Maximum allowable operating pressure (N/mm^2).
p_{corr} = Allowable corroded pipe pressure of a single longitudinal corrosion defect under internal pressure loading (N/mm^2).
$p_{corr,comp}$ = Allowable corroded pipe pressure of a single longitudinal corrosion defect under internal pressure and superimposed longitudinal compressive stresses (N/mm^2).
$p_{corr,,circ}$ = Allowable corroded pipe pressure of a single circumferential corrosion defect (N/mm^2).
p_{corr_j} = Allowable corroded pressure for 'j'th depth increment in a progressive depth analysis of a complex shaped defect (N/mm^2).
p_{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).
$p_{cap,patch}$ = Capacity 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).
p_i = Allowable corroded pipe pressures of individual defects forming a colony of interacting defects (N/mm^2).

1.15. Units

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

2. PART A - PARTIAL SAFETY FACTOR APPROACH

2.1. Introduction

The approach given in Part A is based on the philosophy in the DNV Rules for Submarine Pipeline Systems (DNV'96). 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. ultrasonics)), four different levels of inspection accuracy, and three different reliability levels corresponding to the Safety Class classification in DNV'96.

2.2. Reliability Levels

The partial safety factors and the corresponding fractile values are based on a code calibration and are defined for three reliability levels (corresponding to the Safety Class classification given in DNV'96). The partial safety factors and the fractile values account for uncertainties in pressure, material properties, quality and tolerances in the pipe manufacturing, sizing accuracy of the corrosion defect, etc..

The following Safety Classes are considered (taken from DNV'96 Section 3):

Table 2.1 Safety Class and Target Annual Failure Probability

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

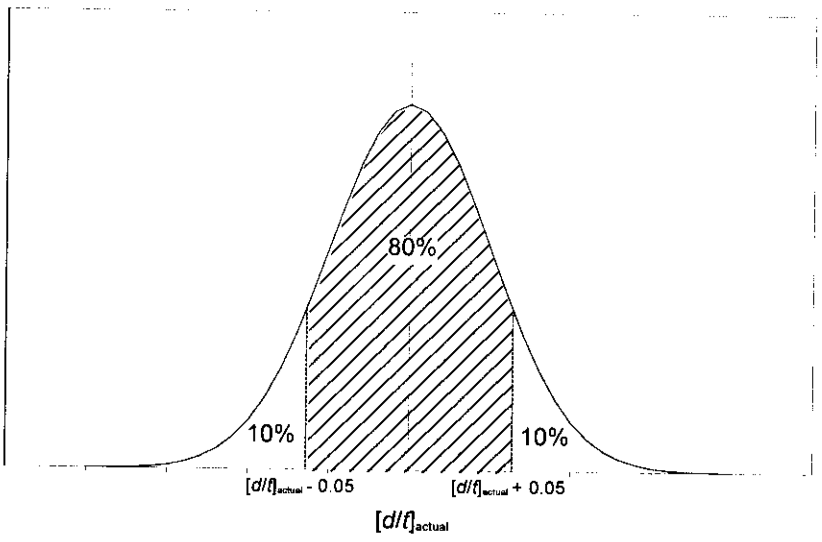
Oil and gas pipelines will normally be classified as Safety Class Normal, where no frequent human activity is anticipated. Safety Class High is used for risers and the parts of the pipeline close to platforms, or in areas with frequent human activities.

2.3. Inspection Accuracy and Standard Deviation

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

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

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



2.4. Partial Safety Factors and Fractile Values

The partial safety factors are given as functions of the sizing accuracy of the measured defect depth, for inspections based on relative depth measurements (such as magnetic flux inspection methods) and inspections based on absolute depth measurements (such as ultrasonic inspection methods). 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 the use of two partial safety factors and corresponding fractile levels for the characteristic values.

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

The application of the partial safety factors is explained in detail in Sections 3 to 6.

2.5. Material Specification

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[21]) for each material grade.

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

$$SMTS = \mathrm{E}[\sigma_u]/1.09 \tag{2.1}$$

The values for the partial safety factors γ_m and γ_{mc} used in the acceptance equation depend upon whether or not additional material requirements are fulfilled. The material properties must be known in detail in order to assess whether or not the additional material requirements are fulfilled. The additional material requirements are given in Table 2.2[1,22]:

Table 2.2 Additional material requirements
$SMYS \le \mathrm{E}[\sigma_y] - 2\mathrm{StD}[\sigma_y]$
$SMTS \le \mathrm{E}[\sigma_u] - 3\mathrm{StD}[\sigma_u]$

1. If only the grade is known, then use a value of *SMTS* corresponding to the material grade and assume that the material requirements are not fulfilled.
2. If the mill certificates show that the additional material requirements are not fulfilled, then use the partial safety factors for materials that do not fulfil the additional requirements. The *SMTS* can be estimated using Equation 2.1 (provided that CoV[σ_u] is less than 0.06), or the value corresponding to the material grade can be used.
3. If the mill certificates show that the additional material requirements are fulfilled, then use the partial safety factors for materials that do fulfil the additional requirements. The *SMTS* can be estimated using Equation 2.1 (provided that CoV[σ_u] is less than 0.06), or the value corresponding to the material grade can be used.

2.6. Partial Safety Factors for Relative Depth Measurement (e.g. Magnetic Flux Measurements)

Partial safety factors are given in Table 2.3 for inspection results based on relative depth measurements (such as magnetic flux inspection methods), where the defect depth measurement and the accuracy are given as a fraction of the wall thickness.

The values for the partial safety factor γ_m in Table 2.3, also include the partial safety factors to be used if the additional material requirements are fulfilled (see Table 2.2):

Table 2.3 Partial Safety Factors γ_m, Relative Depth Measurement

Additional material requirements	Safety Class		
	Low	Normal	High
Not Fulfilled	$\gamma_m = 0.79$	$\gamma_m = 0.74$	$\gamma_m = 0.70$
Fulfilled (see Table 2.2)	$\gamma_m = 0.82$	$\gamma_m = 0.77$	$\gamma_m = 0.73$

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

Table 2.4 Partial Safety Factors, Relative Depth Measurement

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

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

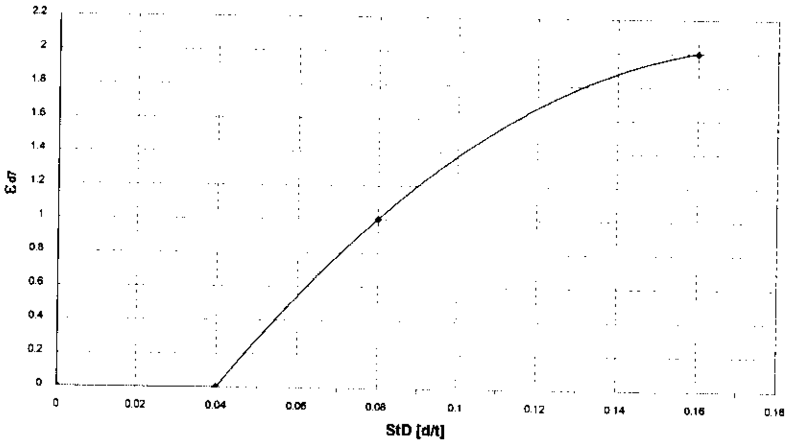
Table 2.5 Polynomial Equations for Partial Safety Factors and Fractile Values (see Table 2.4)

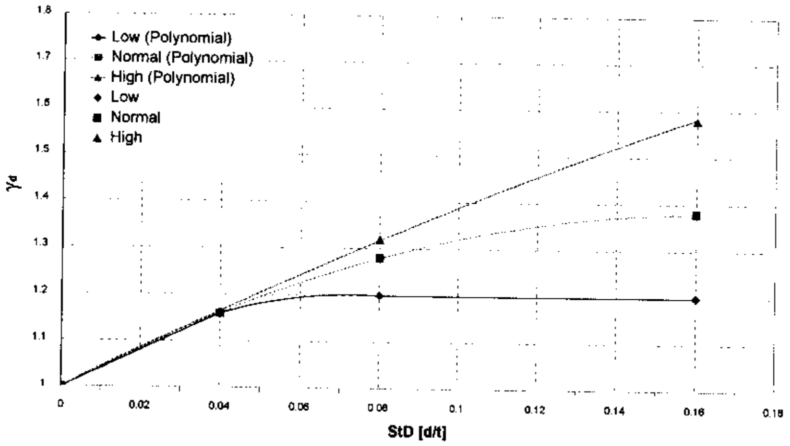
Safety Class	γ_d	**Range**
Low	$\gamma_d = 1.0 + 4.0\,\mathrm{StD}[d/t]$	$\mathrm{StD}[d/t] < 0.04$
	$\gamma_d = 1 + 5.5\,\mathrm{StD}[d/t] - 37.5\,\mathrm{StD}[d/t]^2$	$0.04 \le \mathrm{StD}[d/t] < 0.08$
	$\gamma_d = 1.2$	$0.08 \le \mathrm{StD}[d/t] \le 0.16$
Normal	$\gamma_d = 1 + 4.6\,\mathrm{StD}[d/t] - 13.9\,\mathrm{StD}[d/t]^2$	$\mathrm{StD}[d/t] \le 0.16$

High	$\gamma_d = 1 + 4.3\mathrm{StD}[d/t] - 4.1\mathrm{StD}[d/t]^2$	$\mathrm{StD}[d/t] \leq 0.16$

$$\varepsilon_d = \begin{cases} 0 & \mathrm{StD}[d/t] \leq 0.04 \\ -1.33 + 37.5\mathrm{StD}[d/t] - 104.2\mathrm{StD}[d/t]^2 & 0.04 < \mathrm{StD}[d/t] \leq 0.16 \end{cases}$$

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





2.7. Partial Safety Factors for Absolute Depth Measurement (e.g. Ultrasonic Wall Thickness or Wall Loss Measurements)

Partial safety factors are given in Table 2.6 for inspection results based on absolute depth measurements (such as ultrasonic inspection methods), where the local wall thickness, the defect depth measurement and the accuracy are given directly.

The values for the partial safety factor γ_m in Table 2.6, also include the partial safety factors to be used if the following additional requirements to the material are fulfilled (see Table 2.2):

Table 2.6 Partial Safety Factors γ_m, Absolute Depth Measurement

Additional material requirements	Safety Class		
	Low	Normal	High

Not Fulfilled	$\gamma_m = 0.82$	$\gamma_m = 0.77$	$\gamma_m = 0.72$
Fulfilled (see Table 2.2)	$\gamma_m = 0.85$	$\gamma_m = 0.80$	$\gamma_m = 0.75$

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

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

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

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

$$\mathrm{StD}[l] \leq 20\,\mathrm{StD}[r]$$

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

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

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

$$(d/t)_{\mathrm{meas}} \equiv \mathrm{E}[d/t] = 1 - \frac{\mathrm{E}[r]}{\mathrm{E}[t]}\left(1 + \mathrm{CoV}(t)^2\right)$$

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

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

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

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

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

$$\mathrm{StD}[l] \leq 20\,\mathrm{StD}[d]$$

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

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

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

$$(d/t)_{meas} \equiv \mathrm{E}[d/t] = \frac{\mathrm{E}[d]}{\mathrm{E}[t]}\left(1 + \mathrm{CoV}(t)^2\right)$$

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

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

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

2.8. Partial Safety Factors for Circumferential Corrosion

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

The values for the partial safety factor γ_{mc} in Table 2.7, and η in Table 2.8, also include the partial safety factors to be used if the following additional requirements to the material are fulfilled (see Table 2.2):

Table 2.7 Partial Safety Factors γ_{mc}

Additional material requirements	Safety Class		
	Low	Normal	High
Not Fulfilled	$\gamma_{mc} = 0.81$	$\gamma_{mc} = 0.76$	$\gamma_{mc} = 0.71$
Fulfilled (see Table 2.2)	$\gamma_{mc} = 0.85$	$\gamma_{mc} = 0.80$	$\gamma_{mc} = 0.75$

Table 2.8 Partial Safety Factors η

Additional material requirements	Safety Class		
	Low	Normal	High
Not Fulfilled	$\eta = 0.96$	$\eta = 0.87$	$\eta = 0.77$
Fulfilled (see Table 2.2)	$\eta = 1.00$	$\eta = 0.90$	$\eta = 0.80$

Remark:

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

---e-n-d---o-f---R-e-m-a-r-k---

2.9. Usage Factors for Longitudinal Stress

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

Table 2.9 Usage Factors ξ

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

2.10. The System Effect

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

3. ASSESSMENT OF A SINGLE DEFECT (PART A)

3.1. Requirements

For corrosion defects to be assessed as a single defect (see Figure 3), the defect must an isolated defect. This requirement can be assessed using the method given in Section 4.

3.2. Longitudinal Corrosion Defect, Internal Pressure Loading Only

The allowable corroded pipe pressure of a single defect subject to internal pressure loading only is given by the following acceptance equation.

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

where:

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

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

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

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

The acceptance equation given below is only valid for longitudinal corrosion defects with a circumferential length of less than the longitudinal length. The partial safety factors have not been derived from an explicit probabilistic calibration.

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 allowable corroded pipe pressure of a single longitudinal corrosion defect subject to internal pressure and longitudinal compressive stresses can be estimated using the following procedure:

STEP 1 - Determine the external axial and bending loads on the pipe. Calculate the nominal longitudinal elastic stresses in the pipe, based on the full pipe wall thickness:

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

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

The combined nominal longitudinal stresses is:

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

STEP 2 - If the combined longitudinal stresses are compressive, then calculate the allowable corroded pipe pressure, including the correction for the influence of compressive longitudinal stresses:

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

where:

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

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

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

3.4. Circumferential Corrosion Defects, Internal Pressure and Superimposed Longitudinal Compressive Stresses

The acceptance equation given below is only valid for full circumference corrosion defects with a longitudinal length of less than $1.5t$. The partial safety factors have not been derived from an explicit probabilistic calibration.

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 allowable corroded pipe pressure of a single circumferential corrosion defect can be estimated using the following procedure:

STEP 1 - Determine the external axial and bending loads on the pipe. Calculate the nominal longitudinal elastic stresses in the pipe, based on the full pipe wall thickness:

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

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

The combined nominal longitudinal stresses is:

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

STEP 2 - If the combined longitudinal stresses are compressive, then calculate the allowable corroded pipe pressure, including the correction for the influence of compressive longitudinal stresses:

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

where:

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

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

The longitudinal stress in the remaining ligament is not to exceed ηSMYS, in tension or in compression.

$$|\sigma_L| \le \eta SMYS (1 - (d/t))$$

4. ASSESSMENT OF INTERACTION (PART A)

Adjacent defects can interact to produce a failure pressure that is lower than the failure pressure of either of the isolated defects (if they where treated as single defects). For the case where interaction occurs, the single defect equation is no longer valid and the rules given in Section 5 must be applied.

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

1. The depth of the defect, $\gamma_d (d/t)^*$, is less than 20%.
2. The circumferential spacing between adjacent defects, ϕ:

$$\phi > 360\frac{3}{\pi}\sqrt{\frac{t}{D}} \qquad \textit{(degrees)}$$

3. The axial spacing between adjacent defects, s:

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

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

5. ASSESSMENT OF INTERACTING DEFECTS (PART A)

5.1. Requirements

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

The minimum information required comprises:

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

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:

Remark:

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

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

---e-n-d---o-f---R-e-m-a-r-k---

STEP 1 - For regions where there is background metal loss (less than 10% of the wall thickness) the local pipe wall thickness and defect depths can be used (see Figure 6).

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 spacing of:

$$Z = 360\frac{3}{\pi}\sqrt{\frac{t}{D}} \qquad \textit{(degrees)}$$

STEP 4 - Consider each projection line in turn. If defects lie within ±Z, they should be projected onto the current projection line (see Figure 7).

STEP 5 - Where defects overlap, they should be combined to form a composite defect. This is formed by taking the combined length, and the depth of the deepest defect (see Figure 8). If the composite defect consists of an overlapping internal and external defect then the depth of the composite defect is the sum of the maximum depth of the internal and external defects (see Figure 9).

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

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

where:

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

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

Remark:

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 $n = 1 \ldots N$ and $m = n \ldots N$) is denoted p_{nm}.

---e-n-d---o-f---R-e-m-a-r-k---

STEP 7 - Calculate the combined length of all combinations of adjacent defects (see Figure 10 and Figure 11). For defects n to m the total length is given by:

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

STEP 8 - Calculate the effective depth of the combined defect formed from all of the interacting defects from n to m, as follows (see Figure 10):

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

STEP 9 - Calculate the allowable corroded pipe pressure of the combined defect from *n* to *m* (p_{nm}), (see Figure 8), using l_{nm} and d_{nm} in the single defect equation:

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

where:

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

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

Fully correlated depth measurements:

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

Uncorrelated depth measurements:

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

Remark:

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

The differences between correlated and uncorrelated measurements are discussed in Section 2. Assuming uncorrelated depth measurements will, in general, result in a significantly higher allowable corroded pipe pressure (because $\mathrm{StD}[d_{nm}/t]$ is less than $\mathrm{StD}[d/t]$). In cases where the conditions are not known it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---R-e-m-a-r-k---

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.

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

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 12 for the next section of the corroded pipeline.

6. ASSESSMENT OF COMPLEX SHAPED DEFECTS (PART A)

6.1. Requirements

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

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 length along the defect, should be the maximum depth around the circumference for that 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.

The allowable corroded pipe pressure of a complex shaped defect can be estimated using the following procedure:

Remark:

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

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

At each depth increment the corrosion defect is modelled by an idealised 'patch' containing a number of idealised 'pits'. The 'patch' is the material loss shallower than the given increment depth. The 'pits' are defined by the areas which are deeper than the increment depth, see Figure 12 and Figure 13. The allowable corroded pipe pressure of the 'pits' within the 'patch' is estimated by considering an equivalent pipe of reduced wall thickness. The capacity (failure pressure) of the equivalent pipe is equal to the capacity of the 'patch'.

The idealised 'pits' in the equivalent pipe are assessed using the interacting defect method (see Section 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---o-f---R-e-m-a-r-k---

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:

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

where:

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

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

Fully correlated depth measurements:

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

Uncorrelated depth measurements:

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

Remark:

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

The differences between correlated and uncorrelated measurements are discussed in Section 2. Assuming uncorrelated depth measurements will, in general, result in a significantly higher allowable corroded pipe pressure (because $\mathrm{StD}[d_{ave}/t]$ is less than $\mathrm{StD}[d/t]$). In cases where the conditions are not known it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---R-e-m-a-r-k---

STEP 3 - Divide the profile into equal increments of depth (d_j) (see Figure 12). Each subdivision of the profile separates the profile into an idealised 'patch' portion, shallower than the depth subdivision (i.e. the maximum depth of the 'patch' is d_j), and into 'pits' which are deeper than the subdivision (see Figure 13). The recommended number of increments is between 10 and 50.

STEP 4 - Calculate the average depth of an idealised 'patch' as follows (see Figure 13):

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

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:

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

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

where:

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

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

Fully correlated depth measurements:

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

Uncorrelated depth measurements:

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

Remark:

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

The differences between correlated and uncorrelated measurements are discussed in Section 2. Assuming uncorrelated depth measurements will, in general, result in a significantly higher allowable corroded pipe pressure (because StD[d_{ave}/t] is less than StD[d/t]). In cases where the conditions are not known it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---R-e-m-a-r-k---

STEP 6 - For each of the idealised 'pits', calculate the area loss in the full thickness cylinder, as shown in Figure 13, for the current depth interval, and estimate the average depth of each of the idealised 'pits' from:

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

STEP 7 - Estimate the effective thickness of an 'equivalent' pipe with the same failure pressure as the 'patch', ($p_{cap,patch}$), as calculated in STEP 5 (see Figure 12).

$$t_e = \frac{p_{cap,patch} D}{\left(2(1.09 SMTS) + p_{cap,patch}\right)} \qquad \text{for} \qquad d_j \sum_{i=1}^{i=N} l_i < A_{patch}$$

$$t_e = t \qquad \text{for} \qquad d_j \sum_{i=1}^{i=N} l_i \geq A_{patch}$$

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' ($p_1, p_2, \ldots p_N$) 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:

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

where:

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

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

Remark:

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 $n = 1 \ldots N$ and $m = n \ldots N$) is denoted p_{nm}.

---e-n-d---o-f---R-e-m-a-r-k---

STEP 10 - Calculate the combined length of all combinations of adjacent defects (see Figure 7 and Figure 8). For defects *n* to *m* the total length is given by:

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

STEP 11 - Calculate the effective depth of the combined defect formed from all of individual idealised 'pits' from n to m, as follows (see Figure 7):

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

STEP 12 - Calculate the allowable corroded pipe pressure of the combined defect from n to m (p_{nm}), (see Figure 8), using l_{nm} and $d_{e,nm}$ in the single defect equation:

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

where:

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

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

Fully correlated depth measurements:

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

Uncorrelated depth measurements:

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

Remark:

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

The differences between correlated and uncorrelated measurements are discussed in Section 2. Assuming uncorrelated depth measurements will, in general, result in a significantly higher allowable corroded pipe pressure (because StD[d_{ave}/t] is less than StD[d/t]). In cases where the conditions are not known it is recommended to assume fully correlated depth measurements.

---e-n-d---o-f---R-e-m-a-r-k---

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:

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

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

STEP 15 - 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.

7. PART B - ALLOWABLE STRESS APPROACH

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.

In the equations that follow, the ultimate tensile strength (*UTS*) is quoted. If the measured ultimate tensile strength is not known[4] then the specified minimum ultimate tensile strength should be used (i.e. substitute *SMTS* for *UTS*).

7.2. Total Usage Factor

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

F_1 = ***Modelling Factor***
= **0.9**

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:

$\mathbf{F = F_1 F_2}$

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[4] The measured UTS can be obtained from the results of standard tensile tests on representative pipe specimens, or from mill certificates.

8. ASSESSMENT OF A SINGLE DEFECT (PART B)

8.1. Requirements

For corrosion defects to be assessed as a single defect (see Figure 3), the defect must be an isolated defect. This requirement can be assessed using the method given in Section 9.

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):

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

where:

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

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

$$P_{sw} = F\,P_f$$

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.

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

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

STEP 1 - Determine the external longitudinal and bending loads on the pipe. Calculate the nominal longitudinal elastic stresses in the pipe, based on the full pipe wall thickness:

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

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

The combined nominal longitudinal stresses is:

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

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

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

$$\sigma_L > \sigma_1$$

where:

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

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:

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

where:

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

STEP 4 - Calculate the failure pressure for a longitudinal break, including the correction for the influence of compressive longitudinal stresses (see Figure 1):

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

where:

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

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

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}):

$$P_{sw} = FP_f$$

9. ASSESSMENT OF INTERACTION (PART B)

Adjacent defects can interact to produce a failure pressure that is lower than the failure pressure of either of the isolated defects (if they where treated as single defects). For the case where interaction occurs, the single defect equation is no longer valid and the rules given in Section 10 must be applied.

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

1. The depth of the defect is less than 20% of the wall thickness.
2. The circumferential spacing between adjacent defects, ϕ:

   $$\phi > 360\frac{3}{\pi}\sqrt{\frac{t}{D}} \qquad \textit{(degrees)}$$

3. The axial spacing between adjacent defects, s:

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

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

10. ASSESSMENT OF INTERACTING DEFECTS (PART B)

10.1. Requirements

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

The minimum information required comprises:

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

10.2. Safe Working Pressure Estimate

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

Remark:

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

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

---e-n-d---o-f---R-e-m-a-r-k---

STEP 1 - For regions where there is background metal loss (less than 10% of the wall thickness) the local pipe wall thickness and defect depths can be used (see Figure 6).

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 spacing of:

$$Z = 360\frac{3}{\pi}\sqrt{\frac{t}{D}} \qquad \textit{(degrees)}$$

STEP 4 - Consider each projection line in turn. If defects lie within $\pm Z$, they should be projected onto the current projection line (see Figure 7).

STEP 5 - Where defects overlap, they should be combined to form a composite defect. This is formed by taking the combined length, and the depth of the deepest defect (see Figure 8). If the composite defect consists of an overlapping internal and external defect then the depth of the composite defect is the sum of the maximum depth of the internal and external defects (see Figure 9).

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

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

where:

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

Remark:

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

---e-n-d---o-f---R-e-m-a-r-k---

STEP 7 - Calculate the combined length of all combinations of adjacent defects (see Figure 10 and Figure 11). For defects n to m the total length is given by:

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

STEP 8 - Calculate the effective depth of the combined defect formed from all of the interacting defects from n to m, as follows (see Figure 10):

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

STEP 9 - Calculate the failure pressure of the combined defect from *n* to *m* (P_{nm}), (see Figure 8), using l_{nm} and d_{nm} in the single defect equation:

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

where:

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

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

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

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 13 for the next section of the corroded pipeline.

11. ASSESSMENT OF A COMPLEX SHAPED DEFECT (PART B)

11.1. Requirements

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

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 length along the defect, should be the maximum depth around the circumference for that 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.

11.2. Safe Working Pressure Estimate

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

Remark:

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

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

At each depth increment the corrosion defect is modelled by an idealised 'patch' containing a number of idealised 'pits'. The 'patch' is the material loss shallower than the given increment depth. The 'pits' are defined by the areas which are deeper than the increment depth, see Figure 12 and Figure 13. The failure pressure of the 'pits' within the 'patch' is estimated by considering an equivalent pipe of reduced wall thickness. The failure pressure of the equivalent pipe is equal to the failure pressure of the 'patch'.

The idealised 'pits' in the equivalent pipe are assessed using the interacting defect method (see Section 10).

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

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

---e-n-d---o-f---R-e-m-a-r-k---

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

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

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

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

where:

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

STEP 3 - Divide the profile into equal increments of depth (d_j) (see Figure 12). Each subdivision of the profile separates the profile into an idealised 'patch' portion, shallower than the depth subdivision (i.e. the maximum depth of the 'patch' is d_j), and into 'pits' which are deeper than the subdivision (see Figure 13). The recommended number of increments is between 10 and 50.

STEP 4 - Calculate the average depth of an idealised 'patch' as follows (see Figure 13):

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

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

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

where:

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

STEP 6 - For each of the idealised 'pits', calculate the area loss in the full thickness cylinder, as shown in Figure 13, for the current depth interval, and estimate the average depth of each of the idealised 'pits' from:

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

STEP 7 - Estimate the effective thickness of an 'equivalent' pipe with the same failure pressure as the 'patch', (P_{patch}), as calculated in STEP 5 (see Figure 12).

$$t_e = \frac{P_{patch} D}{(2UTS + P_{patch})} \quad \text{for} \quad d_j \sum_{i=1}^{i=N} l_i < A_{patch}$$

$$t_e = t \quad \text{for} \quad d_j \sum_{i=1}^{i=N} l_i \geq A_{patch}$$

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, ... 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:

$$P_i = \frac{2tUTS}{(D-t)} \frac{\left(1 - \frac{d_{ei}}{t}\right)}{\left(1 - \frac{d_{ei}}{tQ_i}\right)}$$

where:

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

Remark:

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

---e-n-d---o-f---R-e-m-a-r-k---

STEP 10 - Calculate the combined length of all combinations of adjacent defects (see Figure 7 and Figure 8). For defects n to m the total length is given by:

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

STEP 11 - Calculate the effective depth of the combined defect formed from all of individual idealised 'pits' from n to m, as follows (see Figure 7):

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

STEP 12 - Calculate the failure pressure of the adjacent combined pits (P_{nm}), (see Figure 8), using l_{nm} and $d_{e,nm}$ in the single defect equation:

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

where:

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

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

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

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

STEP 15 - The failure pressure of the complex shaped defect (P_f) should be taken as the minimum of that from all of the depth intervals.

STEP 16 - Calculate the safe working pressure (P_{sw}) of the complex shaped defect:

$$P_{sw} = F \, P_f$$

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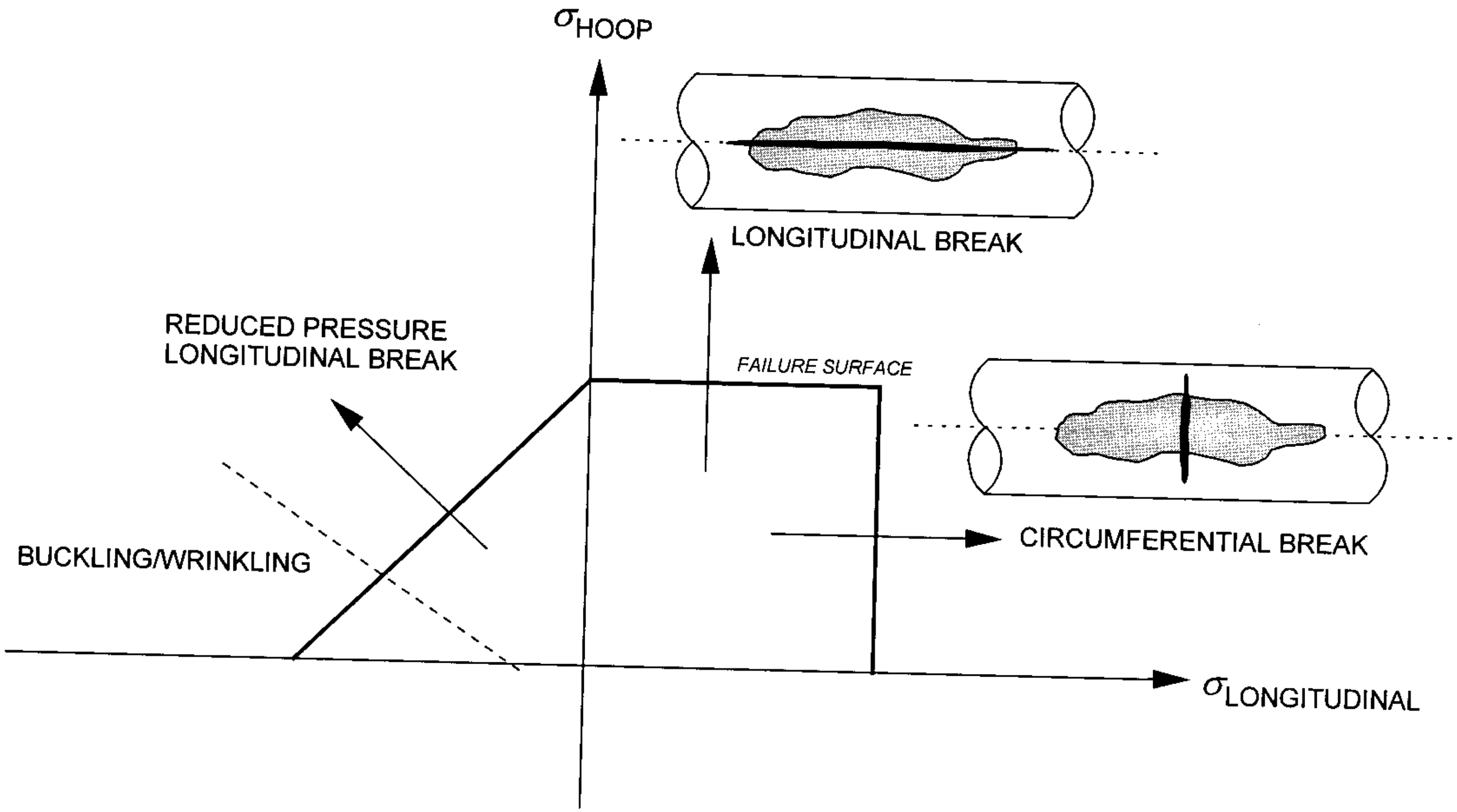


Figure 1 - Influence of Applied Loads on the Failure Mode of a Corrosion Defect

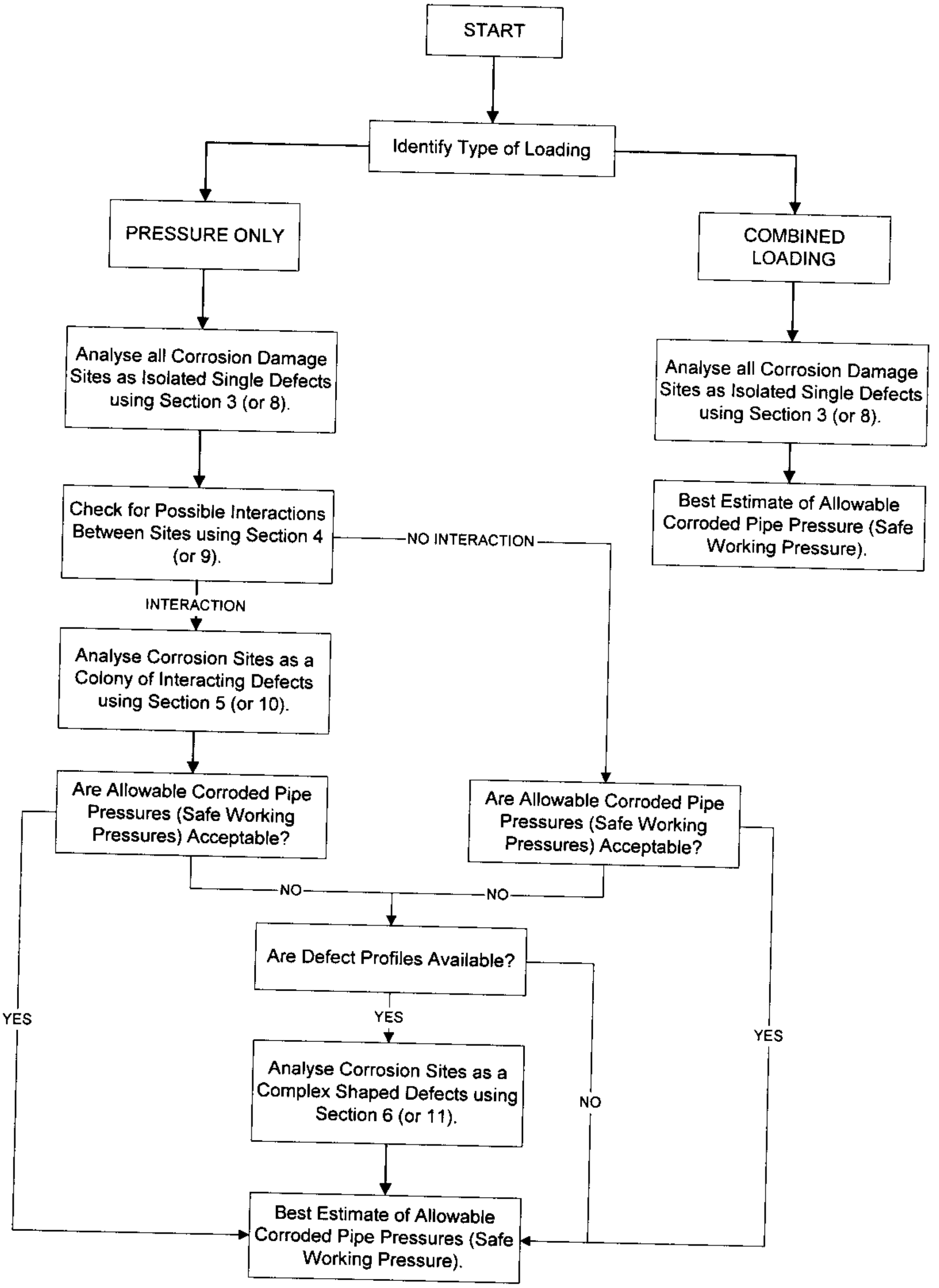


Figure 2 - Flow Chart of the Assessment Procedure.

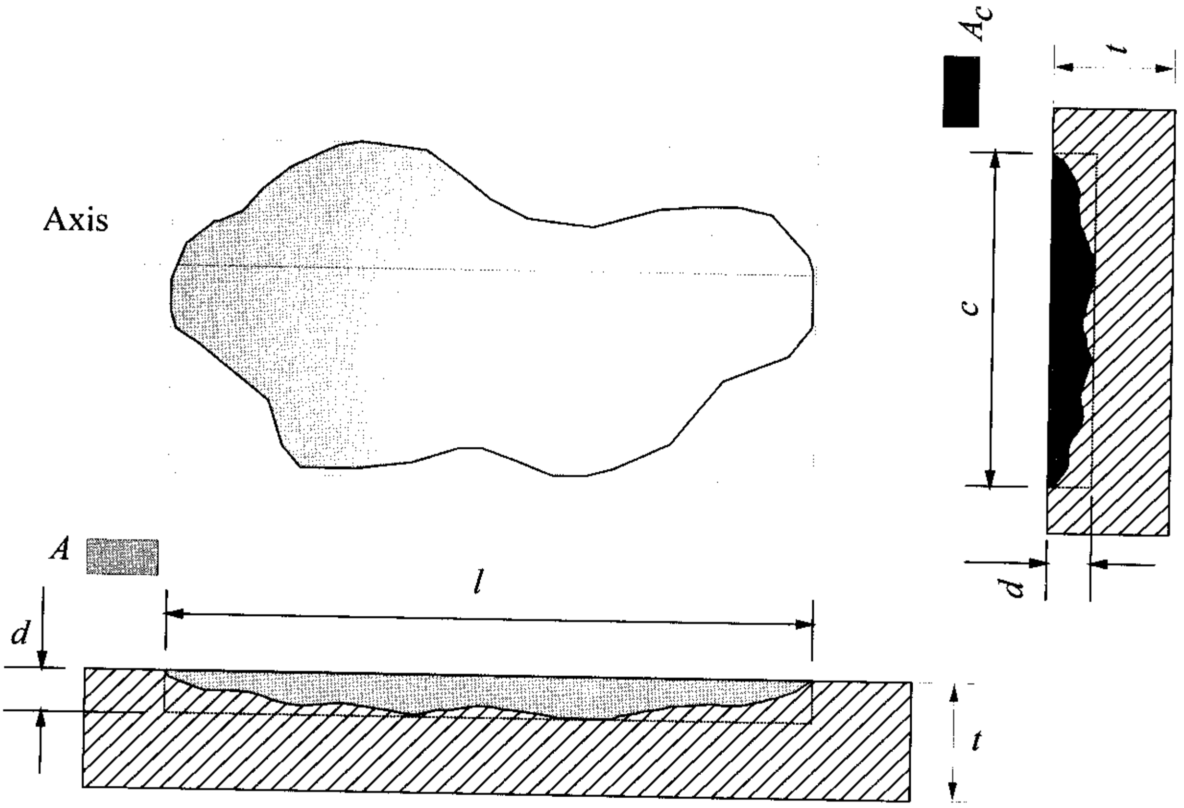
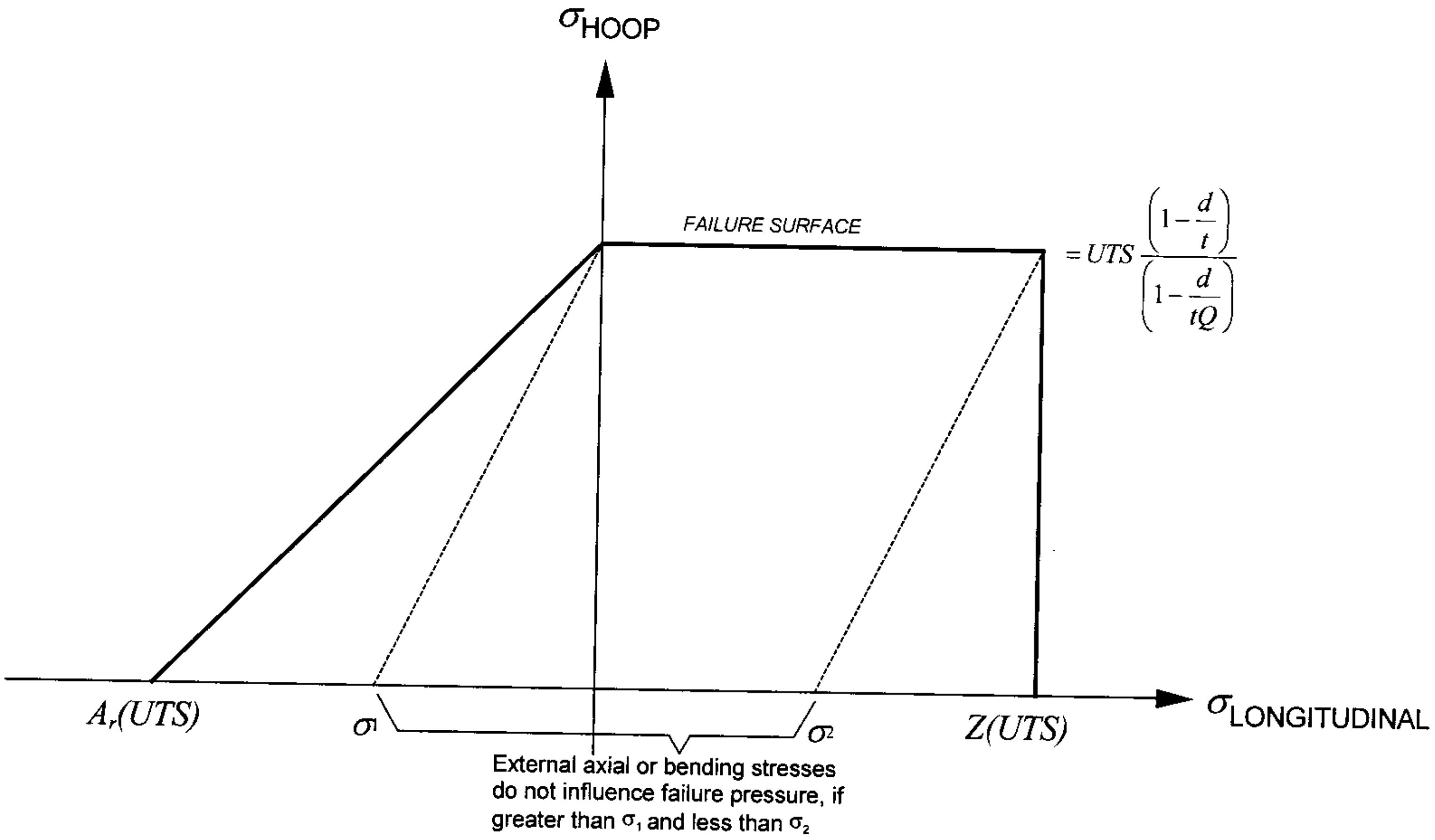


Figure 3 - Single Defect Dimensions.



$$\sigma_1 = -0.5UTS \frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)} \qquad \sigma_2 = UTS\left[Z - 0.5\frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)}\right]$$

Figure 4 - Range of Superimposed Longitudinal and/or Bending Loads which will not Influence the Failure Pressure

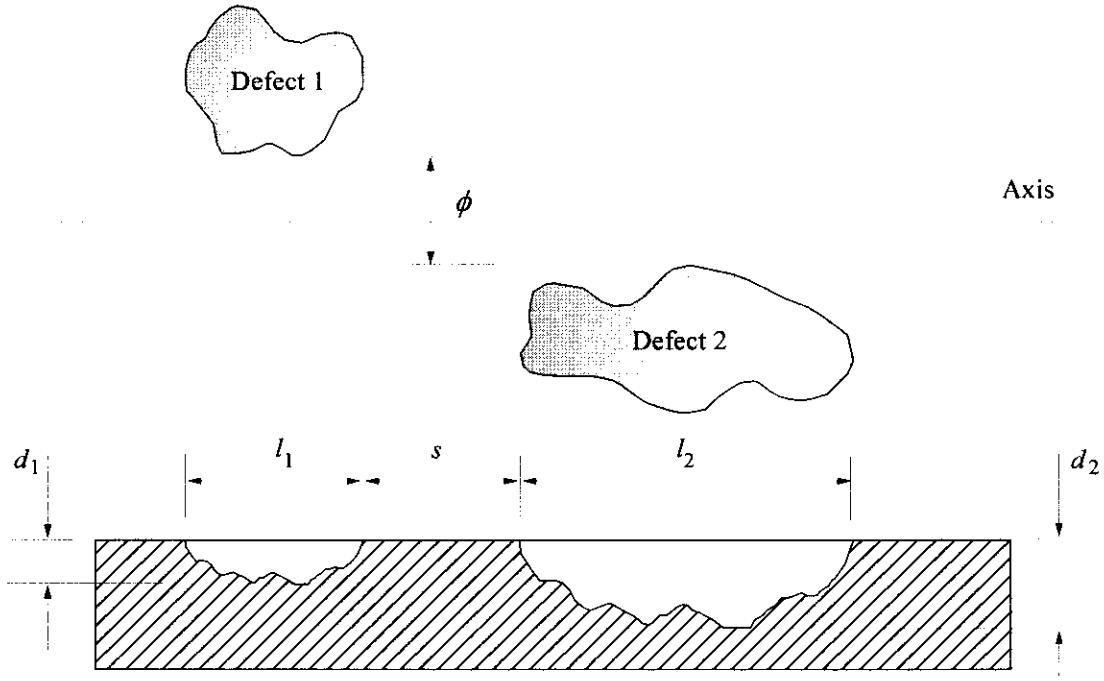


Figure 5 - Interacting Defect Dimensions.

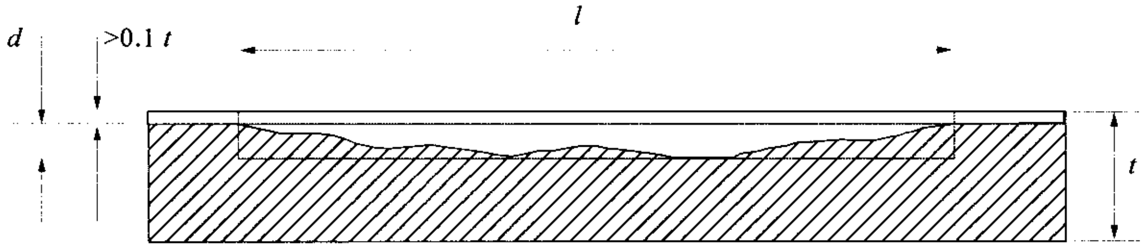


Figure 6 - Corrosion Depth Adjustment for Defects with Background Corrosion.

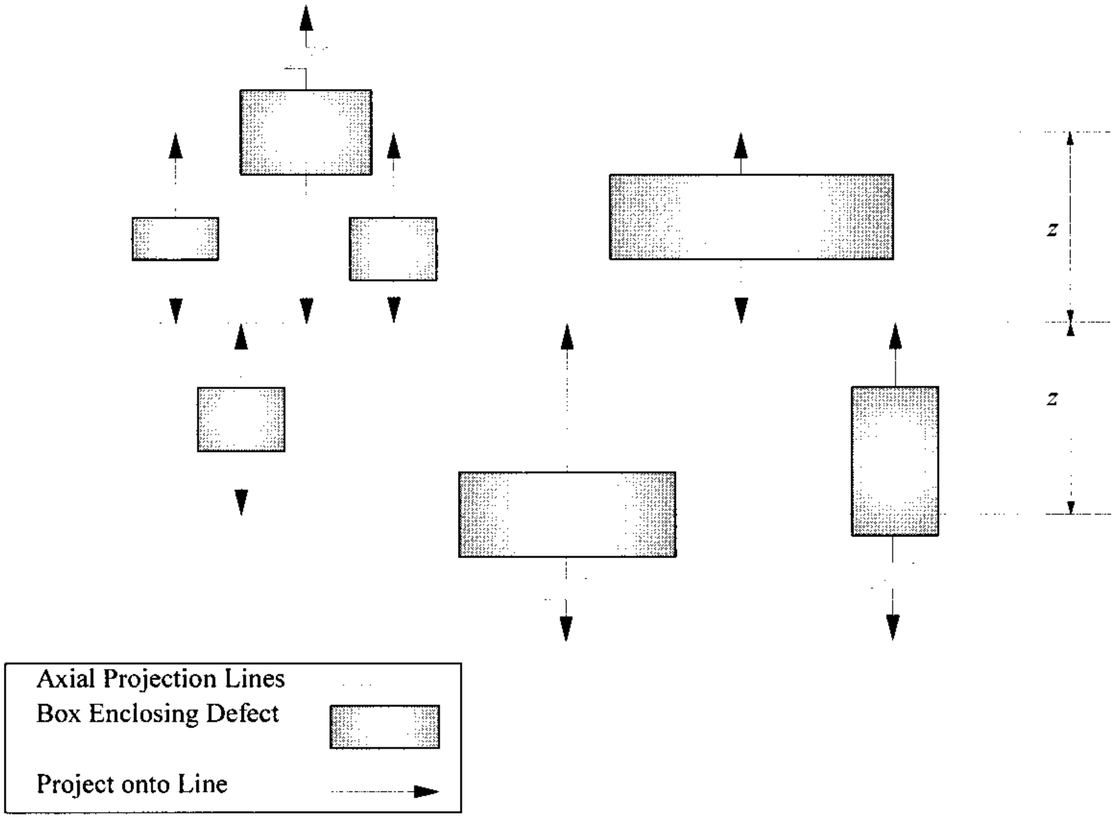


Figure 7 - Projection of Circumferentially Interacting Defects.

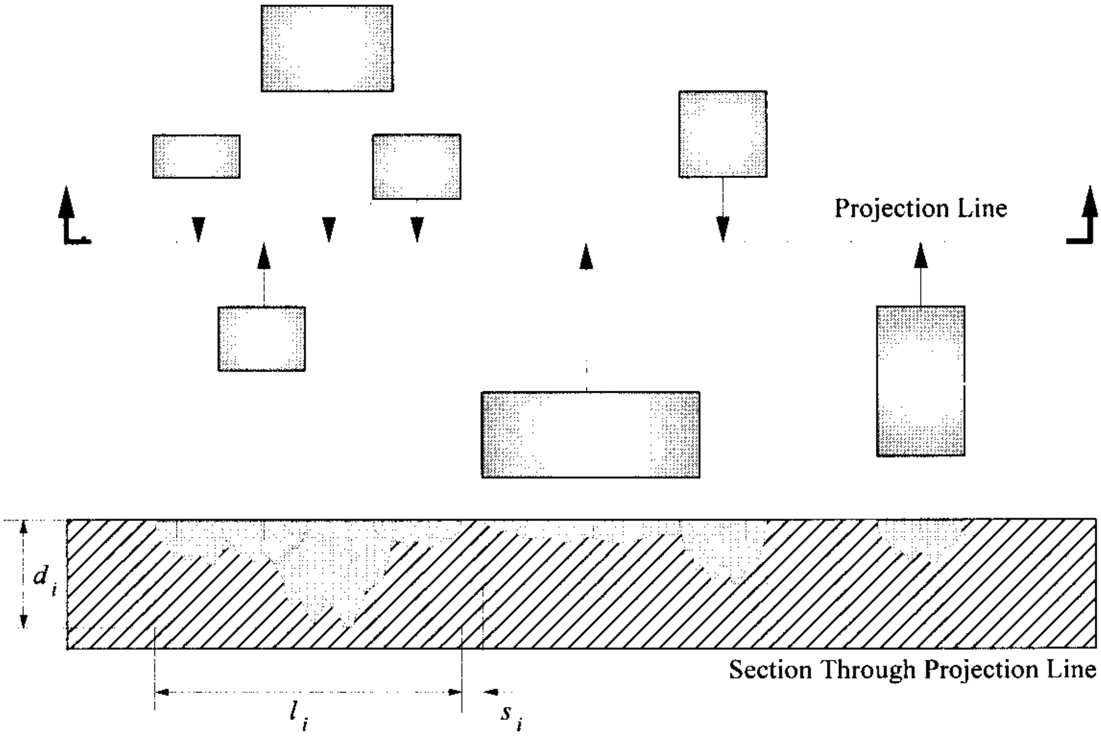


Figure 8 - Projection of Overlapping Sites onto a Single Projection Line and the Formation of a Composite Defect.

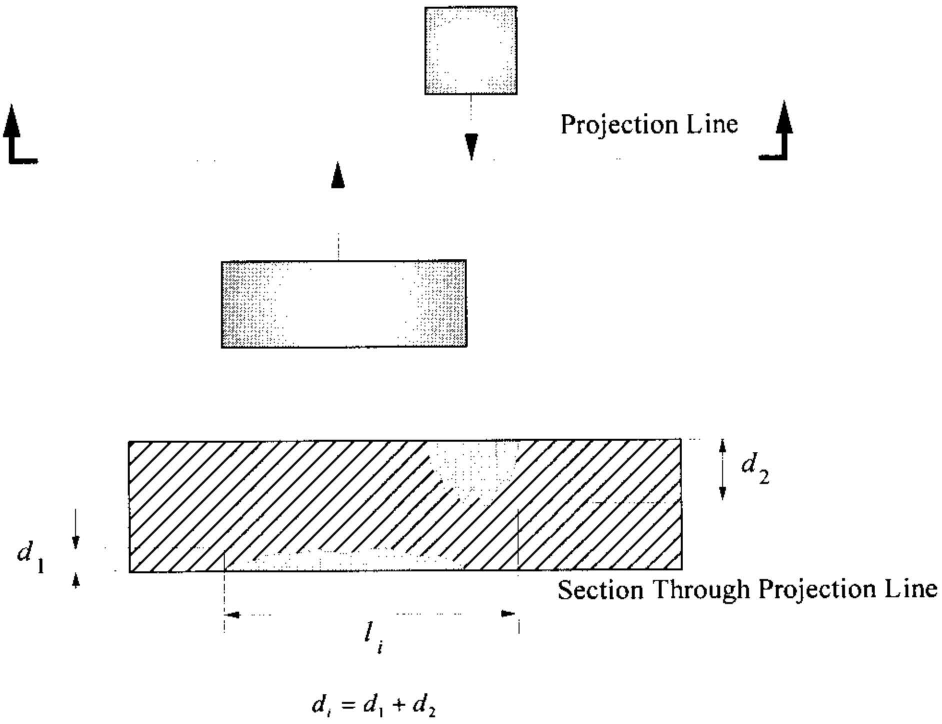
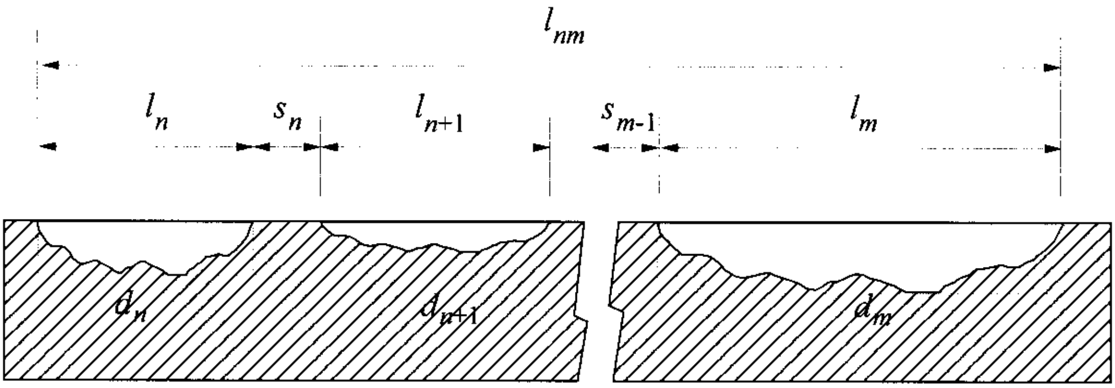


Figure 9 - Projection of Overlapping Internal and External Defects onto a Single Projection Line and the Formation of a Composite Defect.



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

Figure 10 - Combining Interacting Defects.

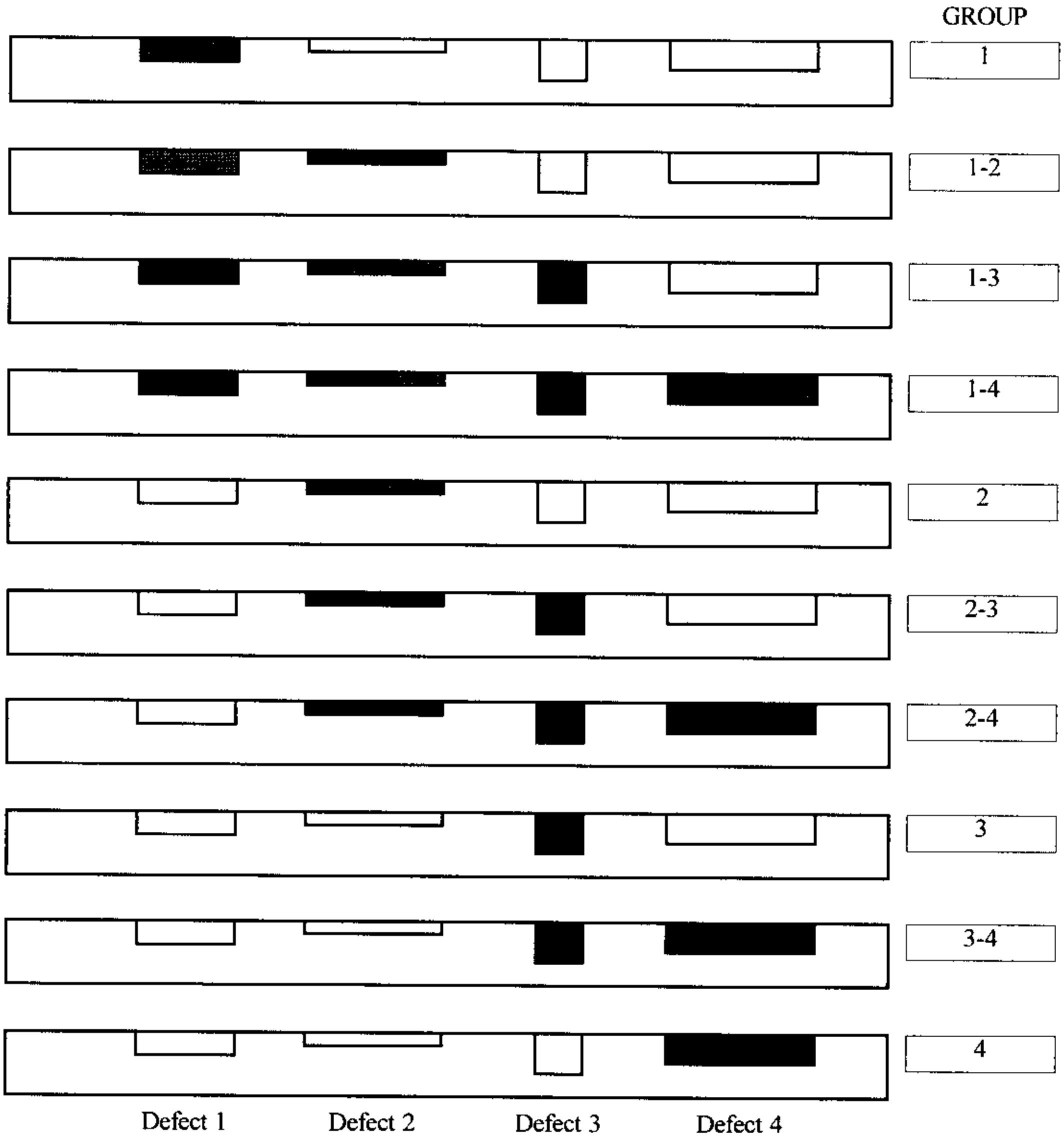


Figure 11 - Example of the Grouping of Adjacent Defects for Interaction to find the Grouping which gives the Lowest Estimated Failure Pressure.

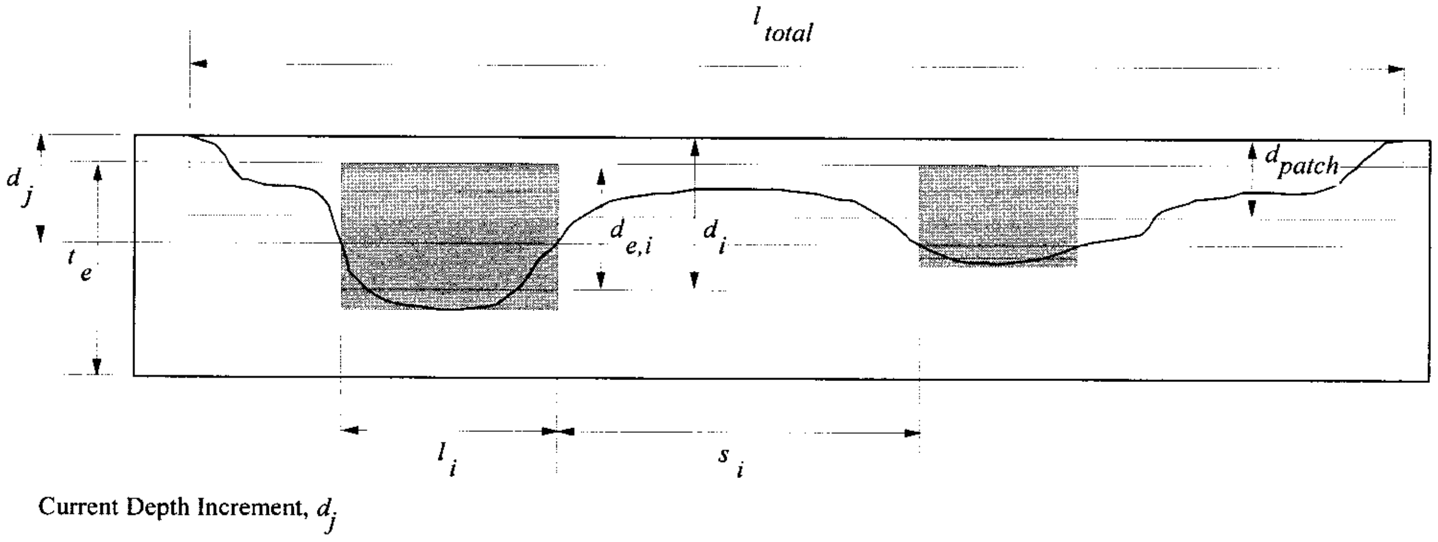


Figure 12 - Subdivision of Complex Shape into Idealised ‘patch’ and ‘pits’.

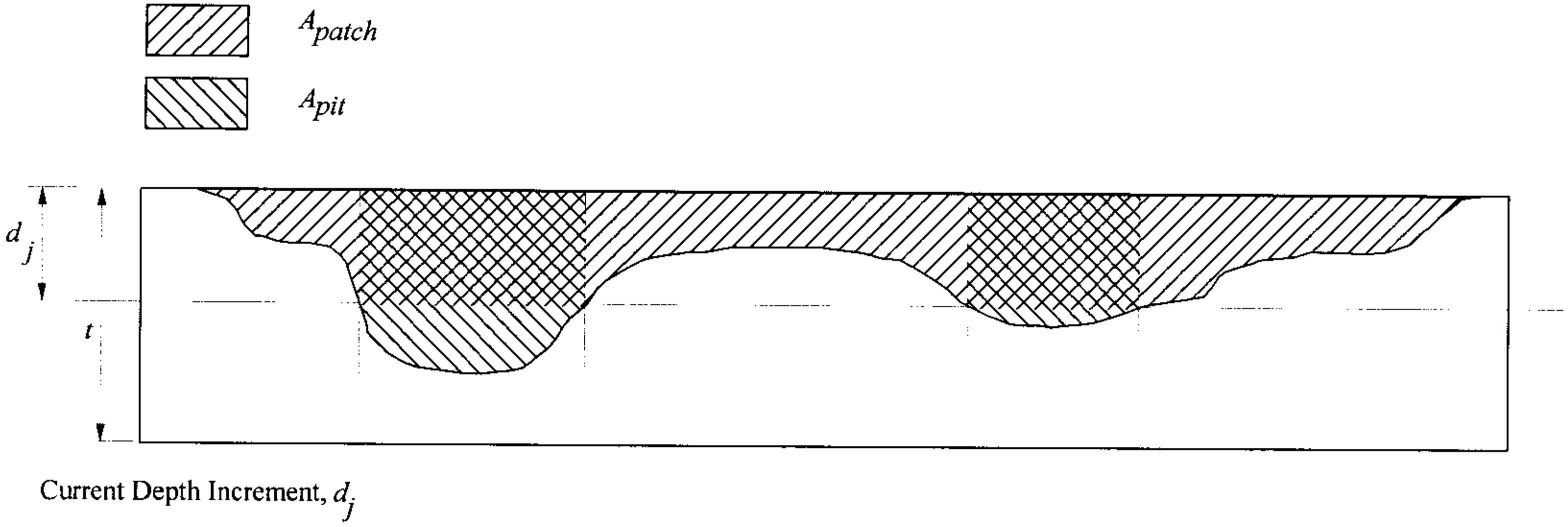


Figure 13 - Definition of A_{patch} and A_{pit} for Subdivision of Complex Shape into Idealised ‘patch’ and ‘pits’.

APPENDIX A - EXAMPLES FOR PART A

A1. Single Defect Assessment

A1.1 Example One

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

The dimensions and material properties are summarised as follows:

Outside Diameter	=	812.8 mm
Wall Thickness	=	19.10 mm
SMTS	=	530.9 N/mm^2 (X65)
Defect Length (max)	=	200 mm
Defect Depth (max)	=	25% of wall thickness

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

Taking the partial safety factors from Table 2.3 and Table 2.4, Section 2.6 (assuming that the additional material requirements are not fulfilled).

$\gamma_m = 0.74$
$\gamma_d = 1.28$
$\varepsilon_d = 1.0$

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

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

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

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

The allowable corroded pipe pressure is 15.94 N/mm^2 (159.4 bar). Therefore, the corrosion defect is acceptable, at the current time, for the maximum allowable operating pressure of 150 bar.

A1.2 Example Two

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

The dimensions and material properties are summarised as follows:

Outside Diameter	=	812.8 mm
Wall Thickness	=	19.10 mm
SMTS	=	530.9 N/mm^2 (X65)
Defect Length (max)	=	200 mm
Defect Depth (max)	=	4.8 mm

The defect dimensions have been taken from the results of an internal inspection using an ultrasonic intelligent pig. The inspection accuracy quoted by the inspection tool provider is that the defect depth will be reported with a ±1 mm tolerance. This sizing accuracy is quoted with a confidence level of 80%.

The maximum allowable operating pressure is 150 bar.

The Safety Class is assumed to be Normal.

Taking the partial safety factors from Table 2.6, Section 2.7 (assuming that the additional material requirements are not fulfilled).

$\gamma_m = 0.77$

$E[t] = 19.10$ mm	$StD[t] = 0.78$ mm	$CoV[t] = 0.04$
$E[d] = 4.8$ mm	$StD[d] = 0.78$ mm	$CoV[d] = 0.16$

From Section 2.7:

$$E[d/t] = \frac{E[d]}{E[t]}\left(1 + CoV(t)^2\right) = 0.2517$$

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

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

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

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

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

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

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

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

The allowable corroded pipe pressure is 17.76 N/mm^2 (177.6 bar). Therefore, the corrosion defect is acceptable, at the current time, for the maximum allowable operating pressure of 150 bar.

A1.3 Example Three

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

The dimensions and material properties are summarised as follows:

Outside Diameter = 219.0 mm
Original Wall Thickness = 14.5 mm
SMTS = 455.1 N/mm^2 (X52)
Defect Length (max) = 200.0 mm
Defect Width (max) = 100.0 mm
Defect Depth (max) = 62% of wall thickness

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

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

The maximum allowable operating pressure is 150 bar.

The Safety Class is assumed to be Normal.

Taking the partial safety factors from Table 2.3 and Table 2.4, Section 2.6 (assuming that the additional material requirements are not fulfilled).

$\gamma_m = 0.74$
$\gamma_d = 1.28$
$\varepsilon_d = 1.0$
$\xi = 0.85$

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

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

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

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

Using the procedure for assessing single defects given in Section 3.3.

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

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

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

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

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

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

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

The allowable corroded pipe pressure is 3.93 N/mm^2 (39.3 bar). This is less than the maximum allowable operating pressure of 150 bar. Therefore the pipeline must be downrated to 39 bar, until the corrosion defect is repaired.

A2. Interacting Defects

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

The basic properties required by the assessment are:

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

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

The maximum allowable operating pressure is 150 bar.

The Safety Class is assumed to be High.

Using the procedure for assessing interacting defects given in Section 5:

Taking the partial safety factors from Table 2.3 and Table 2.4, Section 2.6 (assuming that the additional material requirements are not fulfilled).

$\gamma_m = 0.70$
$\gamma_d = 1.32$
$\varepsilon_d = 1.0$

The defects should be grouped into axial projections as described in Steps 1 to 5 of Section 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/mm^2 and 16.19 N/mm^2 respectively.

Applying the rules for defect interactions in Steps 7 to 9 (Section 10) gives:

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

Assuming that the defect depth measurements are fully correlated:

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

Taking the partial safety factors from Table 2.3 and Table 2.4, Section 2.6 (assuming that the additional material requirements are not fulfilled).

$\gamma_m = 0.70$
$\gamma_d = 1.32$
$\varepsilon_d = 1.0$

Allowable corroded pipe pressure (Step 9) = 14.50 N/mm^2

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

The allowable corroded pipe pressure is 14.50 N/mm^2 (145.0 bar). This is less than the maximum allowable operating pressure of 150 bar. Therefore the pipeline must be downrated to 145 bar, until the corrosion defects are repaired.

Remark:

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

Assuming that the defect depth measurements are uncorrelated:

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

Taking the partial safety factors from Table 2.3 Section 2.6(assuming that the additional material requirements are not fulfilled).

$\gamma_m = 0.70$

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

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

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

Allowable corroded pipe pressure (Step 9) = 16.20 N/mm^2

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

The allowable corroded pipe pressure is 16.19 N/mm^2 (161.9 bar), if it is assumed that the depth measurements are uncorrelated.

---e-n-d---o-f---R-e-m-a-r-k---

A3. Complex Corrosion Defect

The following worked example is for an actual corrosion defect for which the profile has been measured using a depth micrometer.

The pipeline geometry and properties are summarised as follows:

Outside Diameter = 611.0 mm
Wall Thickness = 8.20 mm
SMTS = 517.1 N/mm^2 (X60)

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

The maximum allowable operating pressure is 70 bar.

The Safety Class is assumed to be Normal.

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

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

Table A1 Tabulated Profile for Actual Corrosion Defect.

Using the procedure for assessing single defects given in Section 3.

Total Length = 289.0 mm
Maximum Depth = 2.8 mm

Taking the partial safety factors from Table 2.6, Section 2.7 (assuming that the additional material requirements are not fulfilled).

$\gamma_m = 0.77$

$E[t] = 8.20$ mm	$StD[t] = 0.06$ mm	$CoV[t] = 0.007$
$E[d] = 2.8$ mm	$StD[d] = 0.06$ mm	$CoV[d] = 0.022$

From Section 2.7:

$$E[d/t] = \frac{E[d]}{E[t]}\left(1 + CoV(t)^2\right) = 0.3415$$

$$StD[d/t] = E[d/t]\sqrt{(CoV(d)^2 + 1)(CoV(t)^2 + 1) - 1} = 0.0079$$

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

$$\gamma_d = 1 + 4.6 StD[d/t] - 13.9 StD[d/t]^2 = 1.04$$

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

Allowable Corroded Pipe Pressure = 8.17 N/mm^2

If this complex shaped defect is assessed as a single defect, based on the total length and maximum depth, then the allowable corroded pipe pressure is 8.17 N/mm^2.

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

Single Defect Solution (Steps 1 to 2)

Total Length = 289.0 mm
Maximum Depth = 2.8 mm

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

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

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

Assuming that the defect depth measurements are fully correlated:

$StD[d_{ave}/t] = StD[d/t] = 0.0079$

Taking the partial safety factors from Table 2.5, Section 2.6, and Table 2.6, Section 2.7 (assuming that the additional material requirements are not fulfilled).

$\gamma_m = 0.77$
$\gamma_d = 1.04$

$\varepsilon_d = 0.0$

Allowable Corroded Pipe Pressure = 9.54 N/mm^2

Progressive Depth Analysis (Steps 3 to 15)

The profile was sectioned at 50 levels and the allowable corroded pipe pressure estimated for each increment. Figure A2 shows the variation of the allowable corroded pipe pressure estimate with depth. The minimum allowable corroded pipe pressure estimate was 9.18 N/mm^2. The section depth was 1.09 mm; this corresponds to the natural division between patch and pit which can be seen in Figure A1. The effect of the relatively distinct change in profile at this depth produces a sharp change in the estimated allowable corroded pipe pressure curve, as shown in Figure A2.

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

Step Depth = **1.09 mm**
Patch average area (Step 4) = 286.7 mm^2
Patch length = 289.0 mm
Patch average depth (Step 4) = 0.99 mm

Assuming that the defect depth measurements are fully correlated:

StD[d_{patch}/t] = StD[d/t] = 0.0079

Taking the partial safety factors from Table 2.5, Section 2.6, and Table 2.6, Section 2.7 (assuming that the additional material requirements are not fulfilled).

$\gamma_m = 0.77$
$\gamma_d = 1.04$
$\varepsilon_d = 0.0$

Patch allowable corroded pipe pressure (Step 5) = 9.98 N/mm^2
Patch capacity pressure (Step 5) = 14.17 N/mm^2
Effective reduced thickness (Step 7) = 7.58 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.

StD[d/t] = 0.0079

Taking the partial safety factors from Table 2.5, Section 2.6, and Table 2.6, Section 2.7 (assuming that the additional material requirements are not fulfilled).

$\gamma_m = 0.77$
$\gamma_d = 1.04$
$\varepsilon_d = 0.0$

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

Assuming that the defect depth measurements are fully correlated:

StD[$d_{e,nm}/t$] = StD[d/t] = 0.0079

Taking the partial safety factors from Table 2.5, Section 2.6, and Table 2.6, Section 2.7 (assuming that the additional material requirements are not fulfilled).

$\gamma_m = 0.77$
$\gamma_d = 1.04$
$\varepsilon_d = 0.0$

Number of Pits = 1

Pit	Average Depth (mm)	Average Depth On Reduced Wall (mm)	Length (mm)	Failure Pressure (N/mm^2)
1	1.73	1.1	213	9.18

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) = 9.18 N/mm^2

Step 15 is to estimate the allowable corroded pipe pressure of the complete defect as the minimum of all the minimum estimates for each horizontal step, i.e. the minimum of all Step 13 results (see Figure A2).

Analysis of the defect as a complex profile using the progressive depth method, gives an allowable corroded pipe pressure estimate of 9.18 N/mm^2.

The allowable corroded pipe pressure is 9.18 N/mm^2 (91.8 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.

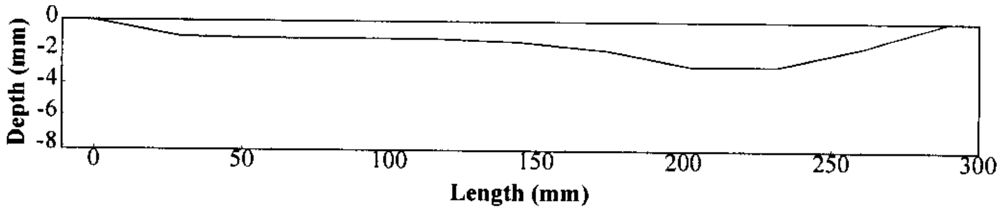


Figure A1 Profile for Actual Corrosion Defect - Example Assessment.

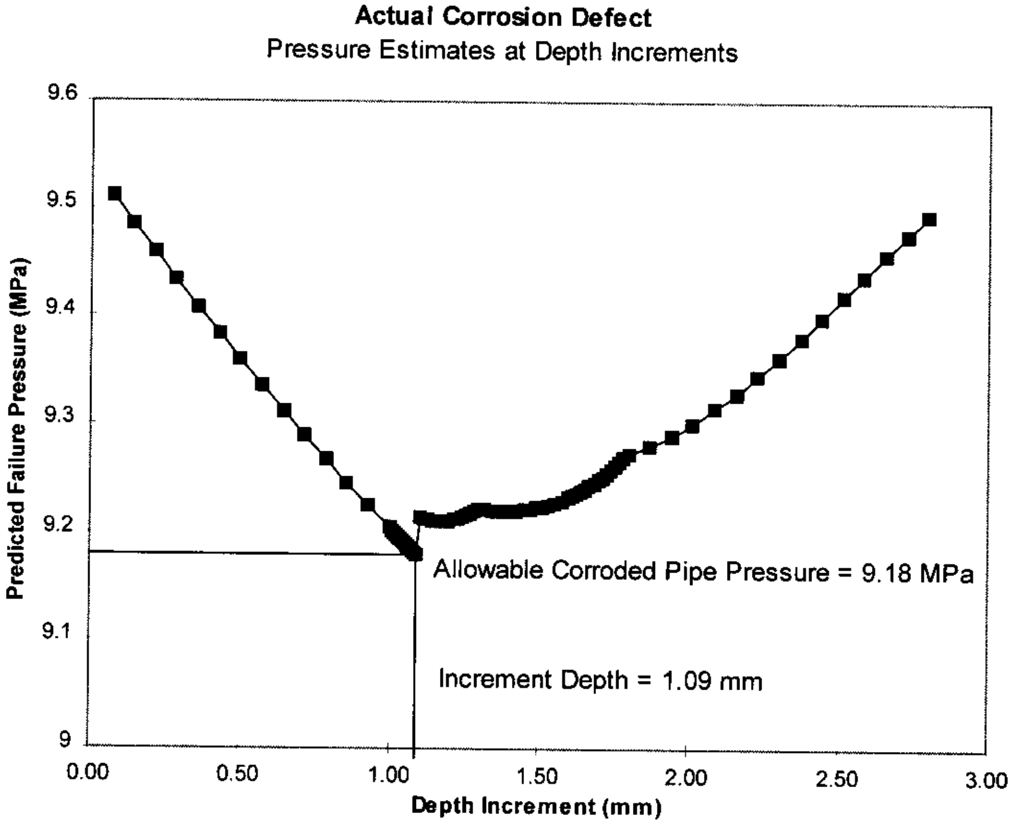


Figure A2 Variations of the Estimated Failure Pressure for Actual Corrosion Defect - Example Assessment.

APPENDIX B - EXAMPLES FOR PART B

B1. Single Defect Assessment

B1.1 Example One

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

The dimensions and material properties are summarised as follows, (the defect reference is B1-1)[B1]:

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

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

Step 1 - Calculate the failure pressure using:

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

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

(This compares with a burst pressure of 20.50 N/mm^2 from a full scale test).

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

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

The safe working pressure is 11.77 N/mm^2.

B1.2 Example Two

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

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/mm^2.

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

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

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

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

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

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

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

$$\sigma_1 = -119.92 \text{ N/mm}^2$$

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

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

$$Q = 1.350$$

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

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

$$H_1 = 0.7277$$

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

Step 5 - Calculate the failure pressure:

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

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

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

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

B2. Interacting Defects

B2.1 Example One

This example is for a pair of rectangular patches 203.2 mm in length and separated axially by 81.3 mm (the defect reference is C2-3/4)[B1]. One defect is 14.2 mm deep and the other is 13.7 mm deep.

The basic properties required by the assessment are:

Outside Diameter	=	812.8 mm
Original Wall Thickness	=	20.1 mm
Measured UTS	=	624.2 N/mm^2

Using the procedure for assessing interacting defects given in Section 10:

The defects should be grouped into axial projections as described in Steps 1 to 5 of Section 10.2.

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

Applying the rules for defect interactions in Steps 7 to 9 (Section 10) for the combined defect gives :

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

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

(In a full scale test, the recorded failure pressure of this defect was 19.60 N/mm^2).

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

B2.2 Example Two

This example is for a pair of rectangular patches 203.2 mm in length and separated axially by 203.2 mm (the defect reference is D2-1/2)[B1]. The defects are 14.1 mm and 14.2 mm deep respectively.

The basic properties required by the assessment are:

Outside Diameter = 812.8 mm
Original Wall Thickness = 20.1 mm
Measured UTS = 624.2 N/mm^2

Using the procedure for assessing interacting defects given in Section 10:

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

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

Applying the rules for defect interactions in Steps 7 to 9 (Section 10) gives:

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

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

(In a full scale test, the recorded failure pressure of this defect was 22.20 N/mm^2).

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

B3. Complex Shaped Defect

B3.1 Example One

This example is an analysis of the failure pressure of a complex shaped defect (see Section 11). The defect is a machined defect (the defect reference is 30-A,A1)[B1]. It is a large rectangular patch containing two adjacent deeper circular defects with semi-elliptical profiles.

The dimensions and material properties are summarised as follows, and a schematic of the defect is given in Figure B1:

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

The defect profile is shown in Figure B2 and the exact depths are tabulated in Table B1.

LENGTH (mm)	DEPTH (mm)
0	0
0	3.9
0.8	7.39
1.6	8.7
2.4	9.61
3.2	10.3
4	10.83
4.8	11.23
5.6	11.53
6.4	11.74
7.2	11.86
8	11.9
163	11.9
169.2	12.42
175.4	13.41
181.5	14.28
187.7	15.04
193.9	15.67
200	16.19
206.2	16.59
212.3	16.87
218.4	17.04
224.5	17.1
230.6	17.04
236.7	16.87
242.8	16.59
249	16.19
255.1	15.67
261.3	15.04
267.5	14.28
273.6	13.41
279.8	12.42
286	11.3
292.2	12.42
298.4	13.41
304.5	14.28
310.7	15.04
316.9	15.67
323	16.19
329.2	16.59
335.3	16.87
341.4	17.04
347.5	17.1
353.6	17.04
359.7	16.87
365.8	16.59
372	16.19
378.1	15.67
384.3	15.04
390.5	14.28
396.6	13.41

402.8	12.42
409	11.9
564	11.9
564.8	11.86
565.6	11.74
566.4	11.53
567.2	11.23
568	10.83
568.8	10.3
569.6	9.61
570.4	8.7
571.2	7.39
572	3.9
572	0

Table B1 Tabulated Profile Complex Shaped Defect

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

Total Length = 572.0 mm
Maximum Depth = 17.1 mm
Failure pressure (Steps 1 through 2) = 10.03 N/mm^2

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

Using the procedure for assessing complex shaped defects given in Section 11:

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 = 7584.66 mm^2
Average depth = 13.26 mm

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

Failure pressure = 16.23 N/mm^2

Progressive Depth Analysis (Steps 3 to 16)

The failure pressure was estimated for approximately 50 steps in a progressive depth analysis. The variation in the failure pressure estimate, with respect to each step, is shown in Figure B3.

Step 3 is to subdivide the defect into horizontal sections or steps 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:

Step Depth = 3.9 mm
Patch average area (Step 4) = 2230.8 mm^2
Patch length = 572.0 mm
Patch average depth (Step 4) = 3.9 mm
Patch failure pressure (Step 5) = 27.68 N/mm^2

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

Number of Pits = 1

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

Effective reduced thickness = 22.1 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	13.26	572	16.23

Pit Interactions Based on the Reduced Thickness Pipe

Start Pit	End Pit	Average Depth In Reduced Wall (mm) (Step 11)	Overall Length (mm) (Step 10)	Failure Pressure (N/mm^2) (Step 12)
1	1	13.26	572	16.23

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 = 16.23 N/mm^2

Step Depth = **13.1625 mm** (This is the section which gives the minimum pressure).
Patch average area (Step 4) = 7053.2 mm^2
Patch length (Step 4) = 572.0 mm
Patch average depth (Step 4) = 12.33 mm
Patch failure pressure (Step 5) = 17.57 N/mm^2
Effective reduced thickness = 12.53 mm

Number of Pits = 2

Pit	Average Depth in Full Thickness Pipe (mm)	Length (mm)	Separation to next pit
1	15.79	101	21.7
2	15.79	101	-

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	101	15.50
1	2	5.61	224	13.40
2	2	6.22	101	15.50

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

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

After all the horizontal step sections have been completed, the failure pressure can be estimated in Step 15.

Step 15 is to estimate the failure pressure of the complete defect, as the minimum of all the minimum estimates for each horizontal step, i.e. the minimum of all Step 13 results (see Figure B3).

Analysis of the defect as a complex profile using the progressive depth method, without the application of a safety factor, gives a failure pressure estimate of 13.40 N/mm^2 from a section depth of 13.1625 mm. This compares with an actual failure pressure of 13.68 N/mm^2.

Step 16 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/mm^2.

B3.2 Example Two

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

The pipeline geometry and properties are summarised as follows:

Outside Diameter = 611.0 mm
Wall Thickness = 8.20 mm
UTS = 571.0 N/mm^2

The defect profile is shown in Figure B4 and the exact depths are tabulated in Table B2.

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

Table B2 Tabulated Profile for Actual Corrosion Defect.

Using the procedure for assessing single defects given in Section 8.

Total Length = 289.0 mm
Maximum Depth = 2.8 mm
Failure pressure (Steps 1 through 2) = 11.86 N/mm^2

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

Using the procedure for assessing complex shaped defects given in Section 11:

Single Defect Solution (Steps 1 to 2)

Total Length = 289.0 mm
Maximum Depth = 2.8 mm

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

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

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

Failure pressure = 13.76 N/mm^2

Progressive Depth Analysis (Steps 3 to 16)

The profile was sectioned at 50 levels and the failure pressure estimated for each increment. Figure B5 shows the variation of the failure pressure estimate with depth. The minimum failure pressure estimate was 13.21 N/mm^2 (the actual failure pressure was 15.4 N/mm^2). The section depth was 1.09 mm; this corresponds to the natural division between patch and pit which can be seen in Figure B4. The effect of the relatively distinct change in profile at this depth produces a sharp change in the estimated failure pressure curve, as shown in Figure B5.

The calculations at the section which 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 = **1.09 mm**
Patch average area (Step 4) = 286.7 mm^2
Patch length = 289.0 mm
Patch average depth (Step 4) = 0.99 mm
Patch failure pressure (Step 5) = 14.35 N/mm^2

Effective reduced thickness (Step 7) = 7.58 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	1.73	1.1	213	13.21

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 = 13.21 N/mm^2

Step 15 is to estimate the failure pressure of the complete defect as the minimum of all the minimum estimates for each horizontal step, i.e. the minimum of all Step 13 results (see Figure B5).

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

The actual burst pressure of the pipe containing the defect was 15.40 N/mm^2.

Step 16 is to calculate the safe working pressure from the estimated failure pressure. Applying the safety factors for a design factor of 0.72:

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

The safe working pressure is 8.56 N/mm^2.

B5. References

B1. FU, B, and VU, D.; *Failure of Corroded Line Pipes - Experimental Testing (Final Technical Report for Line Pipe Corrosion Group Sponsored Project*, Gas Research and Technology Report, Report No. R1803, 1997. Confidential to Project Sponsors.

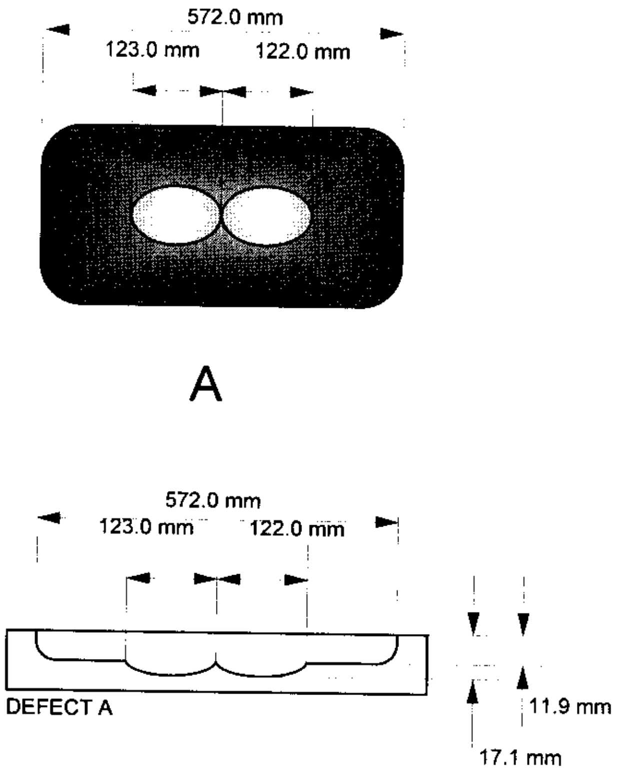


Figure B1 Schematic for Complex Shaped Defect - Example Assessment.

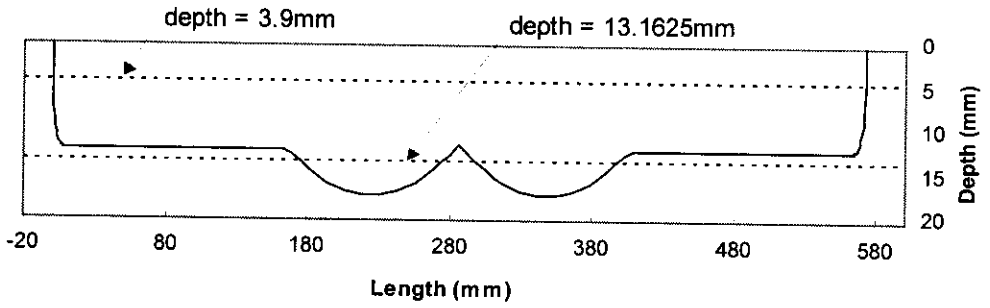


Figure B2 Profile for Complex Shaped Defect - Example Assessment.

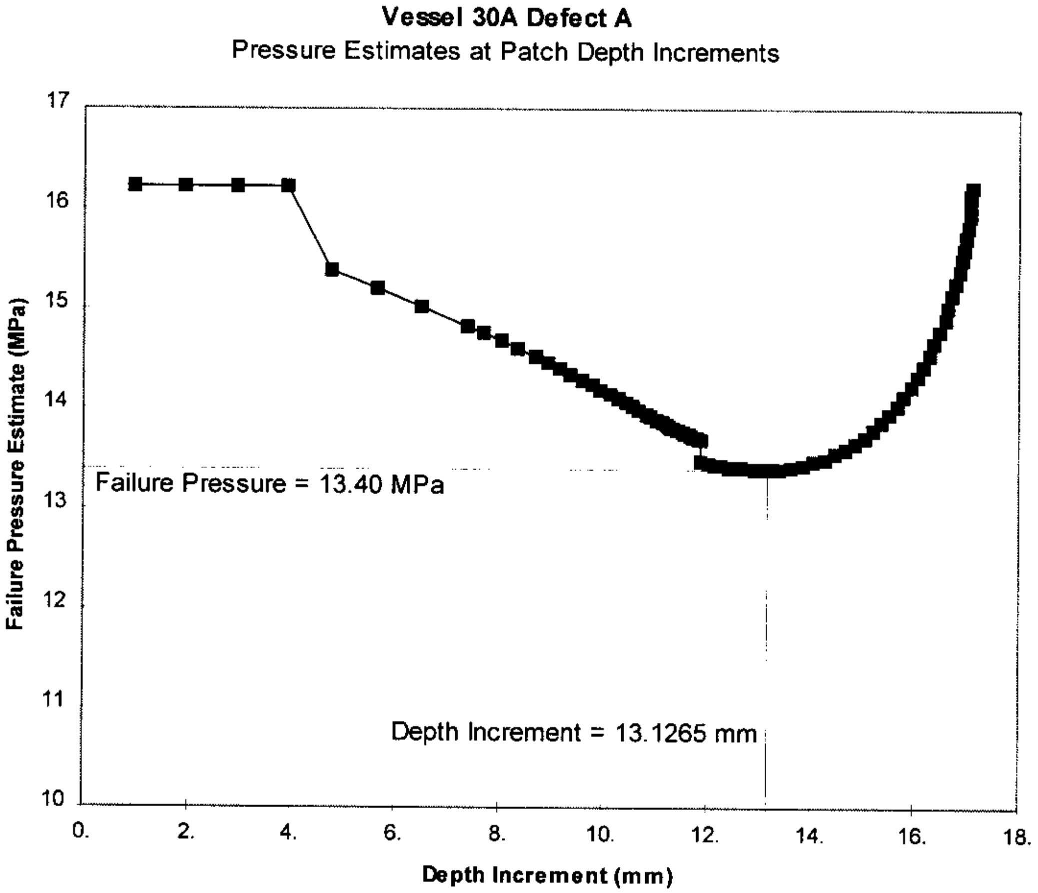


Figure B3 Variations of the Estimated Failure Pressure for Complex Shaped Defect - Example Assessment.

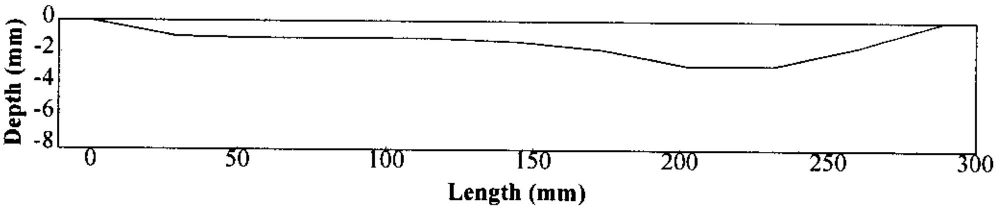


Figure B4 Profile for Actual Corrosion Defect - Example Assessment.

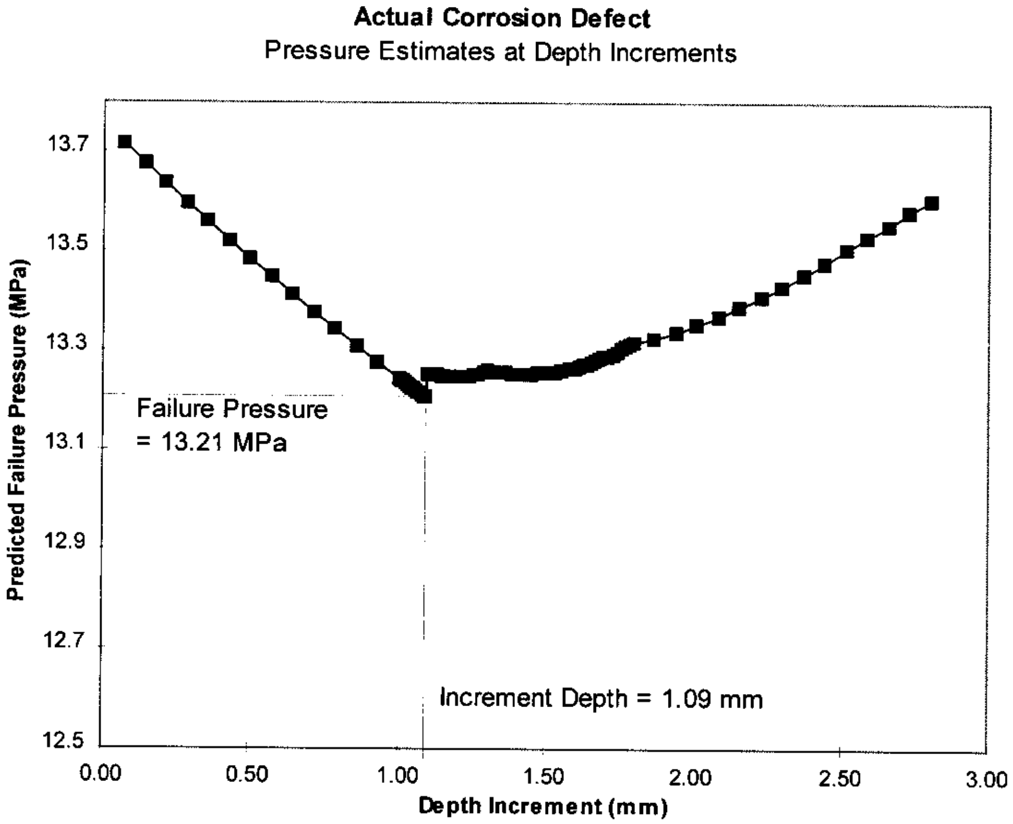


Figure B5 Variations of the Estimated Failure Pressure for Actual Corrosion Defect - Example Assessment.

APPENDIX C - DIFFERENCES BETWEEN CORRELATED AND UNCORRELATED MEASUREMENTS OF WALL LOSS AND THEIR IMPLICATIONS

C1. Introduction

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

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

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

Depth measurements are averaged as part of the assessment of the interactions between pits and the assessment of complex profiles. Correlated measurements give a larger spread in uncertainty during this process than do uncorrelated measurements.

In practice, measurement errors are neither completely uncorrelated or fully correlated, and it is important to take expert advice to decide which assumption is the most appropriate for a particular inspection technique. If it is not possible to establish whether measurements are correlated or uncorrelated, then the most conservative assumption is to assume that they are fully correlated.

C2. Partial Safety Factors for Absolute Depth Measurement (e.g. Ultrasonic Wall Thickness or Wall Loss Measurements)

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

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

$$\mathrm{E}[d/t]=1-\frac{\mathrm{E}[r]}{\mathrm{E}[t]}\exp\left(\mathrm{StD}[Z_2]^2-\rho_{Z_1Z_2}\mathrm{StD}[Z_1]\mathrm{StD}[Z_2]\right)$$

$$\mathrm{StD}[d/t]=\left(1-\mathrm{E}[d/t]\right)\sqrt{\exp\left(\mathrm{StD}[Z_1]^2+\mathrm{StD}[Z_2]^2-2\rho_{Z_1Z_2}\mathrm{StD}[Z_1]\mathrm{StD}[Z_2]\right)-1}$$

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

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

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

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

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

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

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

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

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

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

$$\mathrm{E}[d/t]=\frac{\mathrm{E}[d]}{\mathrm{E}[t]}\exp\left(\mathrm{StD}[Z_2]^2-\rho_{Z_1Z_2}\mathrm{StD}[Z_1]\mathrm{StD}[Z_2]\right)$$

$$\mathrm{StD}[d/t]=\mathrm{E}[d/t]\sqrt{\exp\left(\mathrm{StD}[Z_1]^2+\mathrm{StD}[Z_2]^2-2\rho_{Z_1Z_2}\mathrm{StD}[Z_1]\mathrm{StD}[Z_2]\right)-1}$$

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

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

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

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

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

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

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, $\rho_{Z_1Z_2}$, may be calculated from:

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

APPENDIX D - THE ASSESSMENT OF SINGLE DEFECTS SUBJECT TO INTERNAL PRESSURE PLUS BENDING LOADS AND/OR TENSILE LONGITUDINAL LOADS

D1. Introduction

The method outlined in this Appendix for the assessment of single defects subject to internal pressure plus bending loads and/or tensile longitudinal loads, is based upon the plastic collapse solutions recommended in PD6493[18] and R6[19] for the global plastic collapse of pressurised pipes containing part thickness and part circumferential defects subject to bending and/or tensile longitudinal loads. These approaches have been integrated into the procedures described in the main body of the document for the convenience of users of this document who may wish to consider bending and/or tensile longitudinal loads.

D2. Requirements

For corrosion defects to be assessed as a single defect (see Figure 3), the defect must be clearly defined as an isolated defect without any adjacent defects with which it may interact. This requirement can be assessed from Section 9.

D3. Safe Working Pressure Estimate - Internal Pressure Only

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

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

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

where:

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

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

$$P_{sw} = F\,P_f$$

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

The correction for combined tensile longitudinal and bending loads is based upon a global plastic collapse solution for surface circumferential defects under bending and internal pressure loading. The plastic collapse solution has been validated for crack-like defects, but has not been validated for corrosion damage in large diameter pipeline materials[20].

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

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

STEP 1 - Determine the external longitudinal and bending loads on the pipe. Calculate the nominal longitudinal elastic stresses in the pipe, based on the full pipe wall thickness:

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

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

The combined nominal longitudinal stresses is:

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

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

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

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

where:

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

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

where:

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

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

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

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

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

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

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

where:

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

STEP 4 - If the combined longitudinal stresses are compressive, then estimate the failure pressure for a longitudinal break including the correction for the influence of compressive stresses (see Figure 1):

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

where:

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

STEP 5 - If the combined longitudinal stresses are tensile then estimate the failure pressure for a circumferential break (see Figure 1):

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

where:

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

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

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

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

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

$$P_{sw} = FP_f$$