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COMMERCIAL IN CONFIDENCE

ASSESSMENT OF CORROSION IN LINEPIPE

- BACKGROUND TECHNICAL REPORT

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Report DNV 98-3372
September 1998

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Report GRTC R2491
September 1998

Unified Guidance for The Assessment of Corrosion in Linepipe

Project Close-Out Meeting

10 December 1998

Gas Research & Technology Centre
BG Technology
Ashby Road
Loughborough
Leicestershire, LE11 3GR
United Kingdom

Coffee/Tea and Reception		9.00
1. **Welcome**	C L Jones (BG)	9.30
2. **Project Overview**	B Fu (BG)	9.40
3. **Current Status of DNV Guidance Publication**	O Bjornoy (DNV)	10.10
4. **Basic Methods - Part 1** (1) method for single defect (2) method for defect interaction (3) method for complex-shaped defect (4) method for combined tensile and pressure loading	D Ritchie (Shell)	10.20
Coffee/Tea		11.00
5. **Basic Methods - Part 2** (1) method for combined bending and pressure loading (2) method for combined compression and pressure loading (3) method for circumferential defect	O H Bjornoy (DNV)	11.10
Lunch		12.00
6. **Calibration and Validation of Partial Safety Factors**	G Sigurdsson (DNV)	13.00
7. **Comparisons and Examples**	O Bjornoy (DNV)	14.10
8. **Open Discussion**		14.50
9. **Conclusion**	O Bjornoy (DNV)	15.20
Coffee/Tea and any further discussions		15.40
End of meeting		16.30

** When you arrive please make your way to the Reception Building (approached via the footbridge) where reception desk staff will bring your arrival to the notice of Dr Bin Fu*

JIP PROJECT MEETING

Unified Guidance for the Assessment of Corrosion in Linepipe

Thursday 10 December 1998

Meeting Organiser: Bin Fu (+44 1509 283233)

Conference Room: Brunel 1/2

Name of Quests:

Mr G Senior	BG Transco, Newcastle upon Tyne, UK
Mr A Cosham	Andrew Palmer & Associates, Newcastle upon Tyne, UK
Mr O Bjornoy	Det Norske Veritas, Oslo, Norway
Dr G Sigurdsson	Det Norske Veritas, Oslo, Norway
Mr B McCullough	Health & Safety Executive, London, UK
Mr G Munro	Esso, London, UK
Mr R Ficken	Total Oil Marine, Aberdeen, UK
Dr D Ritchie	Shell, Amsterdam, Netherlands
Mr E Naylor	Saudi Arabian Oil Company, Saudi Arabia
Mr H Garpestad	Phillips Petroleum Company, Tanager, Norway
Mr K A Esaklul	Amoco, Houston, USA
Mr C Smith	Minerals Management Service, Virginia, USA

BG Technology Staff:

Dr A D Batte	(Consultant, Pipeline Engineering)
Dr C L Jones	(Programme Manager, Gas Transmission Technologies)
Dr B Fu	(Project Manager, Structural Integrity)

British Gas Security Classification

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SUMMARY - R & T

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SUMMARY

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TECHNICAL REPORT

ASSESSMENT OF CORROSION IN LINEPIPE
- BACKGROUND TECHNICAL REPORT

REPORT DNV NO. 98-3372

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TECHNICAL REPORT

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TECHNICAL REPORT

Table of Revisions

Rev. No.	Description	Date
01 A	First Draft	01.11.98

Table of Contents

Page

1. CONCLUSIVE SUMMARY

what effects? failure pressure ~~[illegible] pressures~~ of corroded pipe.

Onshore and offshore pipelines pressure capacity. can sometimes experience significant corrosion damage which will reduce their [redacted] Accurate predictions of [redacted] are essential for the determination of design tolerances, integrity assessment and effective maintenance action. The existing ~~corrosion acceptance~~ criterion used in the assessment of corrosion damage, ANSI/ASME B31G, was developed on an empirical basis over 20 years ago~~, although it has since been revised and improved~~. Experience has shown that it can sometimes be significantly over-conservative. In particular, the existing criterion ~~for the assessment of corrosion~~ has an inconsistent safety level for varying degrees of corrosion. Acceptance equations for the assessment of the allowable operating pressures of corroded pipelines that depend on a selected reliability level are therefore desirable.

BG Technology has undertaken a joint industry project which ~~is~~ developed rigorous analysis methods and advanced guidance for the fitness-for-purpose assessment of corroded pipelines. Criteria were developed for predicting the remaining strength of corroded pipes containing single defects, interacting defects and complex shaped defects, supported by extensive experimental tests and numerical analyses.

DNV have undertaken a joint industry project to produce capacity equations and acceptance equations for corroded pipelines with consistent levels of reliability. The project considered longitudinal and circumferential corrosion under internal pressure and compressive longitudinal external loads. Criteria were developed supported by finite element analyses and a series of experimental tests.

The sponsors of the BG Technology and the DNV projects have jointly sponsored a collaborative exercise between BG Technology and DNV to merge the results of the two joint industry projects. ? an unified. The objective of this collaboration was to produce a single guidance document for the assessment of corrosion defects in pipelines that contains methods for the assessment of single, interacting and complex shaped defects, accounts for the compressive external loads, and to produce acceptance equations based on probabilistic calibration, thereby ensuring a consistent ~~level of reliability for varying degrees of corrosion.~~

New guidelines have been developed for more accurate and less over-conservative assessments of pipeline corrosion, particularly for complex-shaped and interacting groups of corrosion. The effect of external compressive loading has been considered. Acceptance equations have been developed which specifically consider the uncertainty associated with the sizing of the defect depth and the material properties, and which give consistent reliability levels for varying degrees of corrosion. These guidelines have the potential to significantly reduce the costs associated with continued operation or repair of pipelines in which in-service corrosion is found.

2. INTRODUCTION

2.1 Background

Oil and gas transmission pipelines can be affected by a range of corrosion mechanisms which may lead to a reduction in structural integrity and eventual failure. The economic consequences of a reduced operating pressure, in terms of lost production or replacement, can be severe. For example major repairs to a pipeline typically cost several hundred thousand dollars on land and several million dollars offshore.

The existing criterion for the assessment of corrosion in linepipe is semi-empirical and was developed over 20 years ago. It was originally developed by Battelle following an extensive programme of full-scale burst tests on pipe sections containing machined slots to represent corrosion defects. The validity of the criterion was subsequently confirmed following a programme of burst tests on pipe sections removed from service and containing real corrosion.

The criterion was embodied in the American pipeline design codes and has become known as the ANSI/ASME B31G criterion. It has subsequently been revised to reduce some of the conservatism in the original formulation, but it is still empirically based on data for thin-walled pipe containing small corrosion areas. Many years experience in the pipeline industry has demonstrated that the existing code can often be over-conservative, resulting in unnecessary repair or replacement; however there have been some instances where the code has been shown to be less conservative or even non-conservative.

Existing methods for assessing corrosion have an inconsistent safety level for varying degrees of corrosion. Acceptance equations for the assessment of allowable operating pressures of corroded pipelines that depend on a selected reliability level are therefore desirable.

BG Technology (part of BG plc) and DNV have both recently undertaken joint industry projects to develop improved methods for assessing corrosion in linepipe. This document is a result of co-operation between BG Technology and DNV to merge the results of their respective joint industry projects and produce unified guidance for the assessment of corrosion in pipelines.

2.2 BG Technology and DNV Research Projects

The BG Technology research project, carried out over three years, 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 smooth metal loss defects was produced. Criteria were developed for predicting the remaining strength of corroded pipes containing single defects, interacting defects and complex shaped defects. The guidance development was supported by extensive experimental tests and numerical analyses to describe the effects of pipe material properties, pipe geometry and defect configuration on failure pressure.

The DNV research project generated a database of 12 burst tests on pipes containing machined corrosion defects, including the influence of superimposed compressive longitudinal and bending 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 to develop an acceptance equation that gave a consistent probability of failure (level of reliability) for various sizes of corrosion defects, different types of inspection and sizing accuracy.

2.3 Objectives

The sponsors of the BG Technology and the DNV projects have sponsored a collaborative exercise between BG Technology and DNV to merge the results of the two joint industry projects. The objective of this collaboration was to produce a single guidance document for the assessment of corrosion defects in pipelines, that contains methods for the assessment of single, interacting and complex shaped defects, accounts for the compressive external loads, and to produce acceptance equations based on probabilistic calibration, thereby ensuring a consistent level of reliability for varying degrees of corrosion.

The combined guidance is presented in a separate report.

2.4 Sponsors of the Programme

The following organisations participated in the project:

Amoco Norway Oil Company
BG plc (Formerly British Gas plc)
BP Exploration
Den norske stats oljeselskap a.s.(Statoil)
Esso Engineering (Europe) Ltd. and Exxon Research & Engineering Company
Minerals Management Service
Norwegian Petroleum Directorate
Petrobras/CENPES/DIPREX
Phillips Petroleum Company and Co-Ventures
Saudi Arabian Oil Company
Shell Expro
Total Oil Marine plc
UK Health and Safety Executive

2.5 Overview

2.5.1 The Guidance Document

This report is a companion document to the unified guidance document which presents the combined guidance for the assessment of corrosion in linepipe. The background and technical basis to the various methods given in the guidance document is described in this report.

The guidance document gives methods for assessing corrosion defects subjected to:

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

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

1. The first approach (Part A of the guidance document) is in accordance with the safety philosophy adopted in the DNV Rules for Submarine Pipeline Systems (DNV'96). 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.
2. The second approach (Part B of the guidance document) 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.

The methods described in Part B of the guidance document are identical to those given in the guidance document produced by the BG Technology joint industry project (Linepipe Corrosion Group Sponsored Project), except that a method for assessing a single corrosion defect under internal pressure and longitudinal compressive stresses has been included.

The methods described in Part A of the guidance document for the assessment of interacting and complex shaped defects, are based on the methods in Part B. Acceptance equations have been developed based on a probabilistic calibration, and partial safety factors have been incorporated.

2.5.2 Capacity Equation for Longitudinal Corrosion

The capacity equation for longitudinal corrosion under internal pressure loading only, was calibrated against a database of over 400 finite element analyses. The capacity equation is used to calibrate the partial safety factors in the acceptance equation for longitudinal corrosion under internal pressure loading only.

2.5.3 Acceptance Equation for Longitudinal Corrosion

The acceptance equation for longitudinal corrosion under internal pressure loading is based on the Linepipe Corrosion Group Sponsored Project (LPC) single defect equation. The acceptance equation incorporates two partial safety factors with corresponding fractile levels for the characteristic parameters, to account for uncertainty associated with the sizing of defect depth and the material properties. The acceptance equation is defined for three different safety levels.

The safety factors and corresponding fractile values for the defect size, are defined as a function of the sizing accuracy of the defect and the applied inspection method.

The acceptance equation for a single corrosion defect under internal pressure loading only has been used in acceptance equations for the assessment of interacting defects and complex shaped defects. No additional probabilistic calibration has been carried out. However, guidance is given on how the uncertainty in the depth of an "equivalent" single defect can be calculated.

The acceptance equation for longitudinal corrosion under combined internal pressure and external loading were developed from the acceptance equation for internal pressure, together with the assumption that the failure surface follows the Tresca yield surface, i.e. the failure surface is assumed to be linear in the compressive loading region. A probabilistic calibration was not carried out explicitly for combined loading.

2.5.4 Circumferential Corrosion

The capacity equation for fully circumferential corrosion was based on the capacity equation for uncorroded linepipe under internal pressure loading.

The acceptance equation for fully circumferential corrosion were based on the burst pressure acceptance equations for uncorroded linepipe together with the assumption that the failure surface follows the Tresca yield surface. No further calibration was carried out.

3. BURST CAPACITY EQUATION FOR LONGITUDINAL CORROSION

3.1 General

The expression for the burst capacity of longitudinal corrosion under internal pressure loading only was based on a combination of a large number of finite element analyses and a series of full-scale tests.

The finite element (FE) analyses were used to derive the burst capacity expression (through a multivariate curve fitting analysis) and the bias between the fitted capacity equation and the FE results. The results of a large number of full scale tests were used to derive the bias between the numerical analysis and the full scale tests.

The finite element analyses used the ABAQUS Finite Element Software (Hibbitt, Karlsson and Sorensen, 1995). The three dimensional FE models incorporated both material non-linearity and large deformation theories. Over 400 FE analyses were carried as part of the BG and DNV projects, to generate a parametric database of failure pressures for variations in pipe geometry (diameter to wall thickness ratio, D/t), corrosion length, corrosion depth and material characteristics.

The failure criterion for the finite element analyses was develop by BG (Fu and Kirkwood, 1995). The finite element analyses were validated using the results of the experimental programme from the BG project consisting of 73 full scale pipe burst tests and 36 ring expansion tests (all internal pressure loading only). The 12 full scale tests carried out within the DNV project considered different combinations of internal pressure loading and external axial and bending loads, only two tests were for internal pressure loading only. A more detailed description of the finite element analyses and the full scale tests are given Fu and Vu (1997), Fu and Noble (1997) and DNV Reliability of Corroded Pipes (1997a).

In addition to the full scale tests from the BG and DNV projects, and results donated by two of the project sponsors, a large number of tests in the published literature were also used to calibrate the capacity equation.

3.2 Capacity Modelling

The expression for the burst capacity for internal pressure loading only, was based on the form of the NG-18 and the B31G equations, both in order to obtain continuity with previous work in the field and because the form of these equations has been found to be suitable for describing the burst capacity. The expressions were, however, calibrated and adjusted in accordance with the results from the finite element analyses and the laboratory burst tests.

The uncertainties associated with the ability of the burst capacity prediction model to represent the "true" burst capacity were defined in two steps;

1. Modelling of the ability of the burst capacity equation to represent the burst capacity obtained from the extensive three dimensional finite element analyses.

2. Modelling of the ability of the finite element analyses to represent the burst capacity obtained from the laboratory tests.

The burst pressure capacity is the expressed as:

$$P_{CAP} = Y_{real} \, Y_{lab} \, Y_{FEA} \, P_{fit} \qquad \text{... 3.1}$$

where

P_{fit} predicted capacity from capacity equation

Y_{FEA} bias in P_{fit} compared to numerical FE analyses

Y_{lab} bias in the numerical FE analyses compared to laboratory tests

Y_{real} bias in the laboratory tests compared to a real pipeline

It should be noted that the bias in the laboratory tests compared to a real pipeline has not been included in the calibration of the capacity equation.

The expression for the burst capacity equation is defined as follows,

$$P_{fit} = P_0 \, R \qquad \text{... 3.2}$$

where P_0 is the plain pipe burst capacity and R is a reduction factor due to the corrosion.

The plain pipe capacity is given as:

$$P_0 = Y_B \, \sigma_u \frac{2t}{D-t}$$

where D is the outer diameter, t is the pipe wall thickness and Y_B (an empirically derived term) accounts for the boundary conditions of the pipe, where:

$$Y_B = \begin{cases} 1.0 & \text{for unconstraint pipe} \\ 1.08 & \text{for constraint pipe} \\ 1.10 & \text{for endcaped pipe} \end{cases}$$

The reduction factor R is given by:

$$R = \frac{1 - \dfrac{d}{t}}{1 - \dfrac{d}{t}\dfrac{1}{M}} H \, Q$$

where:

$$M = \left(1 + a_1 \, X^{a_2}\right)^{a_3}$$

$$X = \frac{L}{\sqrt{Dt}}$$

$$H = \begin{cases} 1 - H_1 H_2 & X \le c_3 \\ 1 & X > c_3 \end{cases}$$

$$H_1\left(\frac{D}{t}, \frac{d}{t}\right) = b_1 + b_2\frac{t}{D} + b_3\frac{d}{D} + b_4\frac{t^2}{D^2} + b_5\frac{dt}{D^2} + b_6\frac{d^2}{Dt}$$

$$H_2\left(\frac{L}{\sqrt{Dt}}, \frac{d}{t}\right) = c_1\, X^{c_2}\left(1 - \frac{X}{c_3}\right)^{c_4}\left(1 + \frac{X}{c_3}\right)\left(\frac{d}{t}\right)^{c_5}$$

$$Q = \begin{cases} 1 - Q_1 Q_2 & X \le e_3 \\ 1 & X > e_3 \end{cases}$$

$$Q_1 = e_1 B^2 + e_2 B$$

$$Q_2 = X^{e_4}\left(1 - \frac{X}{e_3}\right)^{e_5}\left(1 + \frac{X}{e_3}\right)\left(\frac{d}{t}\right)^{e_6}$$

$$B = \frac{1.3\sigma_y}{UTS} - 1$$

where:

d: measured corrosion depth

L: measured corrosion length

D: actual outer pipe diameter

t: actual pipe thickness

σ_y: actual engineering yield strength

σ_u: actual engineering tensile strength

The parameters a_{1-3}, b_{1-6} and c_{1-5} were determined through a calibration of the burst capacity equation to FEA results for one material property (grade X65), but different corrosion depth and lengths, and different *D/t* ratios. The parameters e_{1-6} were obtained by consider different linepipe grades.

3.3 Calibration of Capacity Equation

The expression for the burst capacity equation was calibrated from the FE-analyses. The results from more than 400 finite element analyses were considered, covering the following range of parameter variations:

degree of corrosion depth, d/t :	0.15 - 0.80
degree of corrosion length, $X = L/\sqrt{Dt}$:	0.6 - 30.0
tensile strength, σ_u :	520 - 727 MPa
σ_y/σ_u relationship:	0.7, 0.8, 0.9

The influence of the width of the corrosion was not accounted for explicitly. The calibration study was based on a corrosion width of $3t$. Some FE analyses were, however, carried out on corrosion with a width of $9t$ and $15t$, resulting in minor variations in the predicted burst pressure capacity.

The calibrated fit was obtained by minimising the following expression:

$$\min \sum_{i=1}^{N_{FEM}} \left(\frac{P_{FEM}(i) - P_{fit}(i)}{P_0(i)} \right)^{\lambda} \qquad \text{... 3.3}$$

where N_{FEM} is the total number of FEM analysis results. The penalty exponent $\lambda = 2$ has been applied.

The following results were obtained.

	Parameter					
M	a_1	a_2	a_3			
	0.002	**3**	**1**			
H_1	b_1	b_2	b_3	b_4	b_5	b_6
	1.6	**-3**	**-2**	**2**	**0**	**0**
H_2	c_1	c_2	c_3	c_4	c_5	
	0.4	**1.15**	**25.5**	**8**	**1.5**	
Q_1	e_1	e_2	e_3	e_4	e_5	e_6
	-0.5	**-1**	**16**			
Q_2			e_3	e_4	e_5	e_6
			16	**0.5**	**5.0**	**1.0**

3.4 Burst Capacity Equation

The proposed expression for the burst capacity expression P_{fit} is:

$$P_{fit} = Y_B \sigma_u \frac{2t}{D-t} \left[\frac{1-\frac{d}{t}}{1-\frac{d}{t}\frac{1}{M}} \right] H Q \qquad \text{... 3.4}$$

where

$$M = 1 + 0.002X^3$$

$$H = \begin{cases} 1-H_1 H_2 & X \le 25.5 \\ 1 & X > 25.5 \end{cases}$$

$$H_1\left(\frac{D}{t},\frac{d}{t}\right) = 1.6 - 3\frac{t}{D} - 2\frac{d}{D} + 2\frac{t^2}{D^2}$$

$$H_2\left(\frac{L}{\sqrt{Dt}},\frac{d}{t}\right) = 0.4\,X^{1.15}\left(1-\frac{X}{25.5}\right)^8\left(1+\frac{X}{25.5}\right)\left(\frac{d}{t}\right)^{1.5}$$

$$Q = \begin{cases} 1-Q_1 Q_2 & X \le 16 \\ 1 & X > 16 \end{cases}$$

$$Q_1 = -0.5B^2 - B$$

$$Q_2 = X^{0.5}\left(1-\frac{X}{16}\right)^5\left(1+\frac{X}{16}\right)\left(\frac{d}{t}\right)$$

$$B = \frac{1.3\sigma_y}{UTS} - 1$$

3.5 Prediction Ability of Capacity Equation

The capacity equation for longitudinal corrosion under internal pressure loading only, predicts the finite element results extremely well, resulting in an unbiased factor (Y_{FEA}) with a Coefficient of Variation (CoV) of only 1.5 percent. In Figure 3.1, a comparison between the capacity equation predictions and some of the finite element results (the AP series from the LPC project) is shown, indicating the accuracy of the predictions. Figure 3.2 gives the same comparison and shows that the capacity equation follows the trends in the finite element results.

The bias in the numerical finite element analyses Y_{lab} was obtained by comparing the result of each full scale test with the finite element analysis of the test (this was only done using the test results from the DNV and BG Technology joint industry projects). The finite element analyses predict the results of the tests well, with an unbiased factor with a CoV of 6 percent.

The burst capacity equation was also compared with the results of a large number of full scale tests, including the results of the full scale tests carried out by the DNV and BG Technology joint industry projects, and other tests published in the literature (Chouchaoui and Pick 1992, 1994, and 1996, Coulson and Wolthingham, 1990, Cronin, Roberts and Pick 1996, Hopkins and Jones 1992, and Kiefner and Vieth 1994). Several other references describe burst pressure tests, but do not give sufficient information on the actual material properties or geometry. These other tests have therefore been excluded from the comparison.

A plot of the ratio of the predicted failure pressure (using the capacity equation), based on measured properties, to the actual failure pressure is given in Figure 3.3. Some of the tests included in this figure were on interacting defects or complex shaped defects. In Figure 3.4, the comparison of the capacity equation with the full scale test data is limited to only those tests on single metal loss defects.

The database of full scale tests comprises 138 vessel tests, including both machined defects and real corrosion defects, all tested under internal pressure loading only. The range of test parameters is summarised below:

Pipe Diameter, mm	219.1	to	914.4
Wall Thickness, mm	3.40	to	25.40
D/t ratio	8.6	to	149.4
Grade (API/5L)	Grade B	to	X65
d/t	0.20	to	0.97
$l/(Dt)^{0.5}$	0.44	to	35.14
c/t	0.01	to	21.61

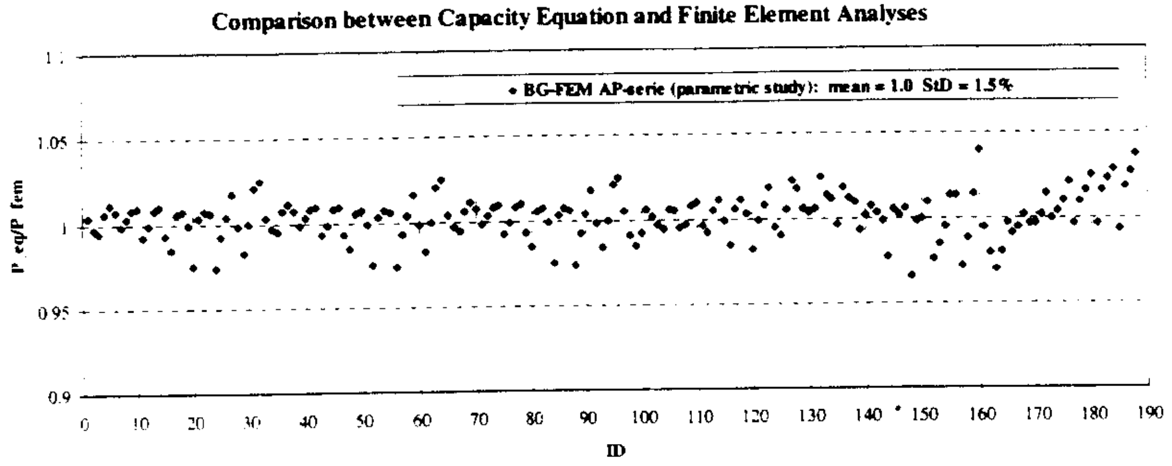

Figure 3.1 Comparison between the Capacity Equation and the Finite Element Analysis Results (BG-FE AP series)

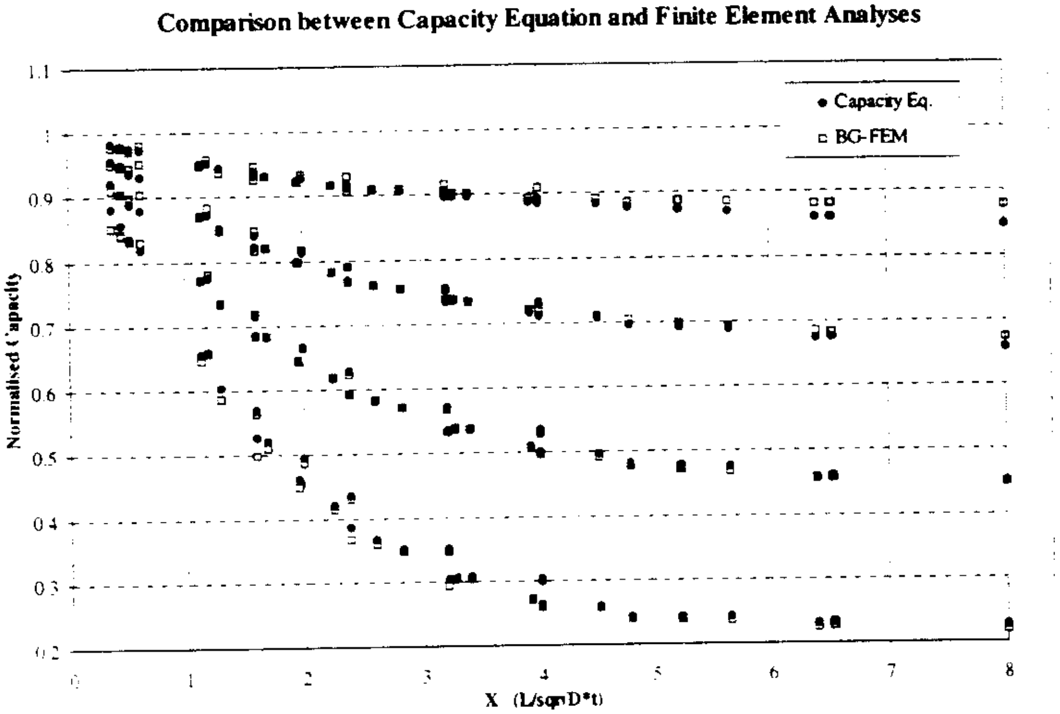

Figure 3.2 Comparison between the Capacity Equation and the Finite Element Analysis Results (for *d*/*t* = 0.2, 0.4, 0.6 and 0.8)

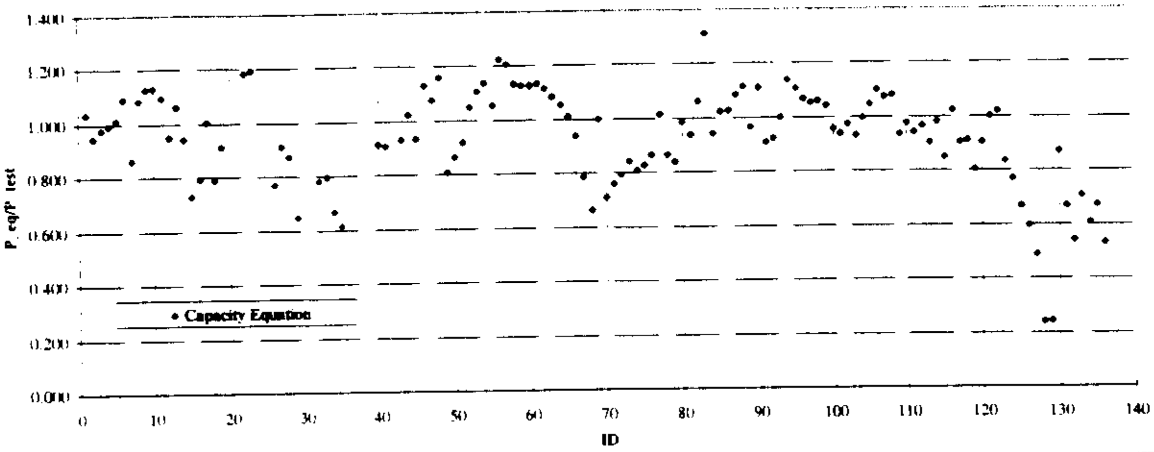

Figure 3.3 Comparison between the Capacity Equation and all Reliable Full Scale Test Data

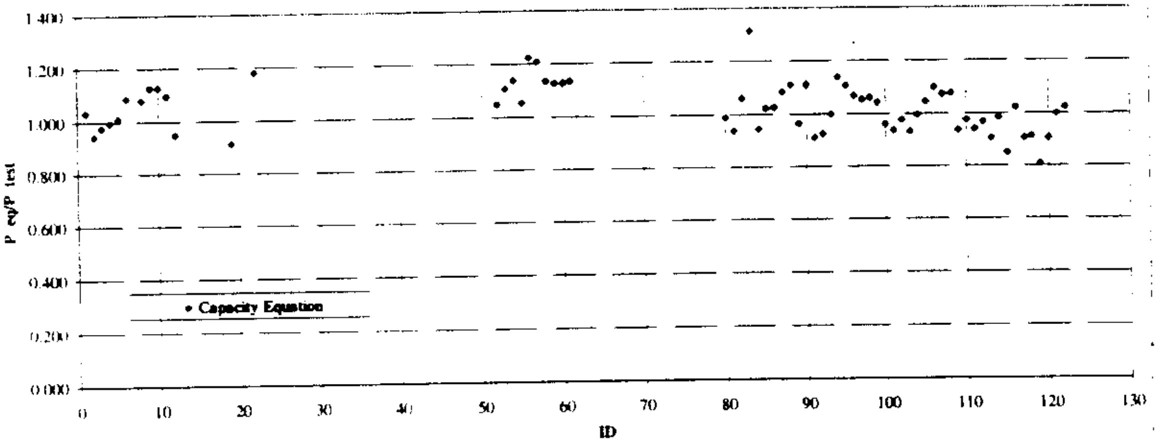

Figure 3.4 Comparison between the Capacity Equation and all Reliable Full Scale Test Data for Single Defects

4. ACCEPTANCE EQUATION FOR LONGITUDINAL CORROSION

4.1 General

The capacity equation predicts the burst capacity of corroded pipes under internal pressure loading only, with a good accuracy for known pipe material properties, pipe geometry, and corrosion characteristics (corrosion depth and length). However, some, or all, of these parameters are difficult to predict without some degree of uncertainty, resulting in a level of uncertainty for the estimated burst capacity of a corroded pipe. These uncertainties should be rationally accounted for in the prediction of the remaining burst capacity.

One way of accounting for uncertainties in the governing parameters is to apply acceptance equations with a known safety level against burst, and where the uncertainties are represented through characteristic values and partial safety factors. In order to avoid unpredictability in the reliability level when applying the acceptance equation, it is important that the acceptance equation has a known and consistent reliability against failure for all levels of corrosion.

In the following section, a probabilistically calibrated acceptance equation for internal pressure loading only, is defined with a consistent level of reliability. Partial safety factors are given to account for uncertainties associated with the sizing of the defect depth and the material properties. This is an example of the LRFD (Load and Resistance Factor Design) methodology.

4.2 Calibration of Partial Safety Factors

The main requirement for the acceptance equation is that is should reflect a defined and uniform reliability level for all design cases within the range of validity.

Typically, different levels of uncertainty will have a varying influence on the estimated capacity from design case to design case. Therefore, the development of acceptance equations satisfying these reliability level requirements requires a detailed knowledge of the uncertainties involved, and how these uncertainties affect the burst capacity of the pipe. The choice of characteristic values representing the uncertain variables, and the associated partial safety factors in the acceptance equation, must therefore be defined with care to assure that all realistic design cases result in a consistent safety level.

The uncertainties affecting the determination of the acceptable annual maximum operating pressure for a corroded pipeline are typically those associated with the determination of:

- the extent of corrosion (depth, length and shape),
- the pipe material characteristics (actual yield strength and tensile strength),
- the pipe geometry (pipe thickness, pipe diameter),
- the operation pressure (daily variations and efficiency of pressure control systems), and
- the accuracy of the applied capacity prediction models.

The modelling of the uncertainties associated with the assessment accuracy of the corrosion prediction depends on the accuracy and reliability of the inspection method and the type of corrosion considered. These uncertainties will significantly affect the estimated burst capacity, and hence the acceptance equation that has been develop is defined for different levels of corrosion inspection accuracy.

The modelling of the uncertainty for the pipe material characteristics, the pipe geometry and the variations in the annual operation pressure are defined based on the findings of the SUPERB project (Jiao et al 1995).

4.2.1 Modelling

In order to cover all realistic design scenarios, more than 200 design cases were considered in the calibration of the burst acceptance equation. The following range of values were considered:

linepipe material grade:	X42 - X80
measured corrosion depths:	$d/t = 0.15 - 0.8$
measured corrosion lengths:	$L/\sqrt{Dt} = 0.6 - 30.0$

The acceptance equations where developed for different levels of corrosion depth inspection accuracy:

- Corrosion depth assessment accuracy;

  80% confidence level: 0, ±5% t, ±10% t, ±20% t (StD.: 0., ≈4% t, ≈8% t, ≈16% t)

The burst acceptance equations for corroded pipes were developed for three different annual failure probabilities (reliability indices), corresponding to the Safety Class classifications given in DNV'96:

- $P_F = 10^{-3}$ (β=3.09) low
- $P_F = 10^{-4}$ (β=3.71) normal
- $P_F = 10^{-5}$ (β=4.27) high

To assure a uniform reliability level for the different design scenarios, the partial safety factors in the acceptance equation were determined by applying probabilistic code calibration procedures using full distribution reliability methods.

The set of partial safety factors to be applied with the selected characteristic values at each defined reliability level, were obtained through an optimisation of a penalty function u:

$$\min \sum_{i=1}^{N_{DES}} u\left(\beta_i - \beta_{target}\right) \qquad \text{... 4.1}$$

where β_{target} is the target reliability index for the specified reliability level and β_i is the reliability index for design case i out of N_{des} design cases.

In order to avoid unconservatism in the acceptance equation, a penalty function was selected such that a higher penalty was given for design cases resulting in a reliability level lower than the target reliability level.

$$u(z) = \begin{cases} (\xi \cdot z)^{\lambda} & z \le 0 \\ z^{\lambda} & z > 0 \end{cases} \qquad \text{... 4.2}$$

In the calibration, the penalty exponent $\lambda = 4$ has been applied, together with the penalty coefficient $\xi = 4$.

The probabilistic calculations were carried out using full distribution probabilistic methods and a first order approximation in the transformed standard normal space, using the general probabilistic analysis program PROBAN (DNV Sesam, 1993).

In order to minimise the computational efforts in the optimisation of the partial safety factors, a five dimensional reliability index response surface was established, using the first order reliability method (FORM), in order to estimate the reliability level for any outcome of the design variables.

4.2.2 Limit State Model

In the modelling of the limit state equation in the calibration of the burst acceptance equation, the following normalised formulation was applied,

$$g = P_{CAP} - P_{INT} \qquad \text{... 4.3}$$

P_{INT} : Annual maximum internal pressure.

P_{CAP} : Burst pressure capacity.

The following limit state function is used in the calibration of the burst code equation,

$$P_{CAP} = Y_{lab} Y_{FEA} Y_B \frac{2t\sigma_u}{D-t} \left[\frac{1-\frac{d}{t}}{1-\frac{d}{t}\frac{1}{M}} \right] H Q \qquad \text{... 4.4}$$

where Y_B, M, H and Q are defined in Section 3.4, and

Y_{FEA} bias in P_{fit} compared to numerical FE analyses

Y_{lab} bias in the numerical FE analyses compared to laboratory tests

4.2.3 Parameters in Limit State Equation

The calibration of the acceptance equation is based on:

- Actual (nominal) values for the pipe characteristics: pipe thickness t and outer diameter D.
- Characteristic description of the material properties: actual yield engineering strength σ_y and actual engineering tensile strength σ_u, defined from 0.5% and 20.0% total strain.
- An empirical description of the burst capacity from Section 3, defined based on a combination of numerical FE analyses and full scale test results.

Parameters for the modelling of the burst limit state equation are given in Table 4.1.

Variable	Description	Distribution	Mean	CoV
P_{INT}	Annual maximum operating pressure	Gumbel	Specified	4.0 %
D	Outer diameter	Deterministic	Actual value	-
t	Pipe thickness	Deterministic	Actual value	-
σ_y	Yield strength	Normal	Actual measured	4.0 %
σ_u	Tensile strength	Normal	Actual measured	4.0 %
L	Corrosion length	Normal	Measured value	Specified
d/t	Corrosion depth	Normal	Measured value	Specified
Y_{FEA}	Fit to FE results	Normal	1.0	1.5 %
Y_{lab}	Fit to laboratory results	Normal	1.0	6.0 %

Table 4.1 Parameters in the modelling of the burst limit state equation

The inclusion of the uncertainty associated with the variation of the pipe thickness was considered. However, probabilistic studies indicated that this uncertainty had a limited influence on the determination of the annual maximum operating pressure for corroded pipes, and that a description of the pipe wall thickness by the nominal thickness was sufficient[1].

4.3 Burst Acceptance Equation

The format of the burst acceptance equation corresponds to the LPC single defect failure equation. This format has been adopted in order to remove the need to revalidation of the single defect equation and the methods for assessing interacting defects and complex shaped defects.

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[1] Note that the corrosion depth was defined in relative terms, i.e. d/t not d.

Based on the results of the probabilistic calibration, the proposed burst acceptance equation for the allowable operating pressure of a corroded pipeline is.

$$E[P_{INT}] = \gamma_m SMTS \frac{2t}{D-t} \frac{1-\gamma_d (d/t)^*}{1-\dfrac{\gamma_d (d/t)^*}{M}} \qquad \text{... 4.5}$$

where

$$M = \sqrt{1.0 + 0.31 \cdot X^2}$$

$$X = \left(\frac{L_{meas}}{\sqrt{Dt}} \right)$$

$$(d/t)^* = E[d/t] + \varepsilon_d Std[d/t]$$

The superscript * defines the use of characteristic values and corresponding partial safety factors. 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 the model prediction.

γ_d: Partial safety factor for the corrosion depth.

ε_d: Factor for determining a fractile level for the corrosion depth.

The characteristic values to be applied in the burst acceptance equation in order to defined the mean value of the maximum allowable operating pressure of the corroded pipeline are:

$(d/t)_{meas}$	measured relative corrosion depth (the mean value of d/t is approximated by the measured value)
L_{meas}	measured corrosion length
D	nominal outer diameter
t	nominal pipe thickness
$SMYS$	Specified Minimum Yield Strength
$SMTS$	Specified Minimum Tensile Strength

The partial safety factors and the corresponding fractile levels for the characteristic values are determined through probabilistic calibrations to achieve the required target reliability levels. Two different levels of material quality (defined as the coefficient of variation of the tensile strength) have been considered:

1. Standard Material Requirements

The specified minimum tensile strength (SMTS) is defined as

$$E[\sigma_u] = 1.09\text{SMTS}$$

This implies that $CoV[\sigma_u] \leq 0.06$.

2. Additional Material Requirements

The specified minimum yield strength (SMYS) and the specified minimum tensile strength (SMTS) are defined as (SUPERB project (Jiao et al 1995)).

$$\text{SMYS} = \text{E}[\sigma_y] - 2\text{StD}[\sigma_y]$$

$$\text{SMTS} = \text{E}[\sigma_u] - 3\text{StD}[\sigma_u]$$

This implies that $CoV[\sigma_u] \leq 0.03$.

4.4 Partial Safety Factors

Inspection methods such as a magnetic flux leakage intelligent pig, give the depth of a corrosion defect relative to the nominal wall thickness of the pipe. Methods such as ultrasonic wall thickness probes, give a direct measurement of the depth of corrosion, or the thickness of the remaining ligament. 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.

The calibrated values for the partial safety factors and the associated fractile levels for the characteristic values in the acceptance equation, as a function of the required reliability level and the corrosion depth sizing accuracy, are given in the following sections for relative depth measurements and absolute depth measurements.

4.4.1 Partial Safety Factors for Relative Depth Measurement

The partial safety factors γ_m and γ_d, and the fractile value ε_d, are defined as follows:

Additional material requirements	Safety Class		
	Low	Normal	High
Not Fulfilled	$\gamma_m = 0.79$	$\gamma_m = 0.74$	$\gamma_m = 0.70$
Fulfilled (see Section 4.3)	$\gamma_m = 0.82$	$\gamma_m = 0.77$	$\gamma_m = 0.73$

Table 4.2 Partial Safety Factors γ_m, 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	$\gamma_d = 1.20$ $\varepsilon_d = 2.0$	$\gamma_d = 1.38$ $\varepsilon_d = 2.0$	$\gamma_d = 1.58$ $\varepsilon_d = 2.0$

Table 4.3 Partial Safety Factors and Fractile Values, Relative Depth Measurement

The following polynomial equations can be used to determine the appropriate partial safety factors and fractile values given in Table 4.3, for intermediate values of StD[*d*/*t*].

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

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

Table 4.4 Polynomial Equations for Partial Safety Factors and Fractile Values

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

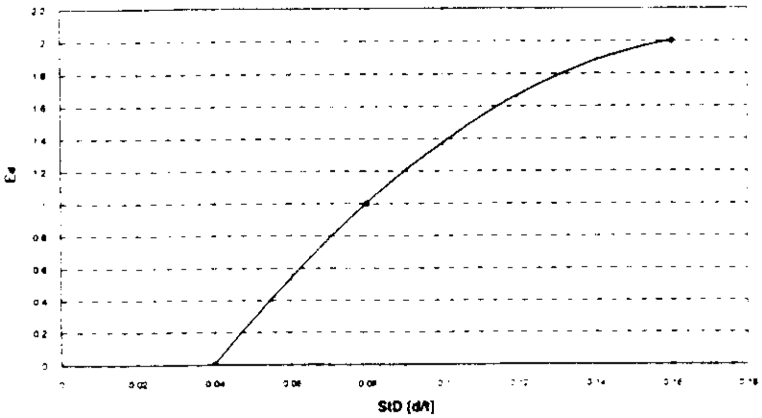

Figure 4.1 Variation of Partial Safety Factor ε_d with StD[d/t].

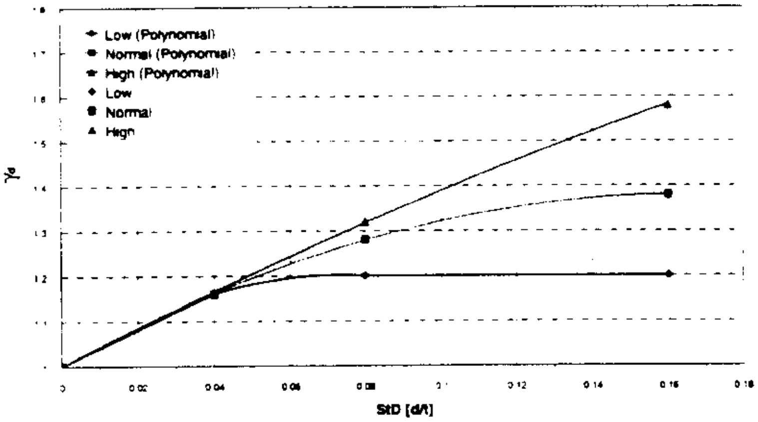

Figure 4.2 Variation of Partial Safety Factor γ_d with StD[d/t].

4.4.2 Partial Safety Factors for Absolute Depth Measurement

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 (see Table 4.3 and Table 4.4). The partial safety factor γ_m is different, however, because for absolute measurements it is assumed that the pipe wall thickness around the corroded area is measured with at least the same accuracy as the corrosion depth.

The partial safety factor γ_m is defined as follows:

Additional material requirements	Safety Class		
	Low	Normal	High

Not Fulfilled	$\gamma_m = 0.82$	$\gamma_m = 0.77$	$\gamma_m = 0.72$
Fulfilled (see Section 4.3)	$\gamma_m = 0.85$	$\gamma_m = 0.80$	$\gamma_m = 0.75$

Table 4.5 Partial Safety Factors γ_m, Absolute Depth Measurement

The partial safety factor γ_d and the fractile value ε_d are defined in terms of StD[*d*/*t*], having been derived for relative depth measurements. It is necessary to transform the absolute depth measurements into relative depth measurements in order to determine the values of γ_d and ε_d. The equations for calculating the StD[*d*/*t*] of the relative corrosion depth from the known uncertainties in the absolute measurements are given below.

The choice of equation depends upon whether or not the correlation between the measurement of the remaining ligament thickness (*r*) and the uncorroded wall thickness (*t*) is known. 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. In such cases it is appropriate to assume that there is no correlation (i.e. the correlation coefficient is assumed to be equal zero). This assumption results in a simpler set of equations for determining StD[*d*/*t*]. The derivation of the equations given below assumes that *d*, *r* and *t* have LogNormal distributions.

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

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

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

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

Known Correlation

For known correlation, the mean value, E[*d*/*t*], and the standard deviation, StD[*d*/*t*], of the relative corrosion depth may be written as:

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

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

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:

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

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

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

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

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

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

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

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:

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

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

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

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

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

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

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

Known Correlation

For known correlation, the mean value, E[*d*/*t*], and the standard deviation, StD[*d*/*t*], of the relative corrosion depth may be written as:

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

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

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:

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

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.

4.5 Interaction

4.5.1 Background and Validation

A method for assessing the interaction of adjacent corrosion defects under internal pressure loading only, was developed as part of the Linepipe Corrosion Group Sponsored Project (LPC). This method is described in the GRTC R1806, 1997 and GRTC R1960, 1997. The interaction rules and the method for assessing interacting defects have been incorporated directly into the combined guidance document.

The effect of using the assessment methods for interacting defects is shown by comparing Figure 4.3 and Figure 4.4. The defects shown in the comparison consist of artificial single, interacting and complex shaped defects. The comparison uses the measured material properties, with no safety factors.

In Figure 4.3, the LPC single defect equation has been used to predict the failure pressure of the artificial defects, irrespective of whether they are actually interacting or complex shaped defects. In Figure A5, the predicted failure pressure has been calculated using either the interacting defect method or the complex shaped defect method. The effect of using the interacting defect method is to raise all the estimated failure pressures (shown in filled circles) to the failure line (i.e. unity), except for two defects (see Section 4.6 for a more detailed explanation).

4.5.2 Correlated and Uncorrelated Wall Loss Measurements and the Assessment of Interacting Defects

When assessing interacting defects using the partial safety method, it is important to establish whether the defect depth measurements are correlated or uncorrelated. This is necessary because part of the assessment of interacting defects involves the calculation of the effective depth of the combined defect formed from all of the combinations of interacting defects (Step 8 of the assessment method).

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.

The implementation of the method for accounting for correlated and uncorrelated measurements when assessing interacting defects is described below. No additional probabilistic calibration has been carried out.

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

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

The acceptance equation in Step 9 requires the characteristic value of the relative effective corrosion depth, defined as $(d_{nm}/t)^*$.

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

The value of $\mathrm{StD}[d_{nm}/t]$ depends upon whether the corrosion measurements are correlated or uncorrelated. It can be shown that for fully correlated depth measurements:

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

and that for uncorrelated depth measurements:

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

where:

$E[X]$	expected value of random variable X
$\mathrm{StD}[X]$	standard deviation of random variable X
d_i	depth of an individual defect forming part of a colony of interacting defects
d_{nm}	average depth of a defect combined from adjacent defects n to m in a colony of interacting defects
l_i	longitudinal length of an individual defect forming part of a colony of interacting defects
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
t	pipe wall thickness

4.6 Complex Shaped Defects

4.6.1 Background and Validation

A method for assessing the complex shaped defects under internal pressure loading only, was developed as part of the Linepipe Corrosion Group Sponsored Project (LPC). This method is described in the GRC R1806, 1997 and GRC R1960, 1997. The complex shaped defect assessment method has been incorporated directly into the combined guidance document.

The effect of using the complex shaped defect assessment method is shown by comparing Figure 4.3 and Figure 4.4. In Figure 4.3, the LPC single defect equation has been used to predict the failure pressure of the artificial defects. In Figure A5, the predicted failure pressure has been calculated using either the interacting defect method or the complex shaped defect method. The effect of using the complex shaped defect assessment method is to raise all the estimated failure pressures (shown in filled circles) to the failure line (i.e. unity).

There are two interacting defects for which the complex shaped defect assessment method gives a better estimate of the failure pressure than the interacting defect assessment method. These are, respectively, two touching pits and a colony of four touching pits. The complex treatment takes into account the actual profile of the defects and therefore compensates for the added area.

4.6.2 Correlated and Uncorrelated Wall Loss Measurements and the Assessment of Complex Shaped Defects

When assessing complex shaped defects using the partial safety method, it is important to establish whether the defect depth measurements are correlated or uncorrelated. This is necessary because part of the assessment of complex shaped defects involves the calculation of the effective depth of the combined defect formed from all of the combinations of interacting defects (Step 11) for each given depth increment (i.e. part of the interacting defect assessment method is used for the assessment of complex shaped defects). Furthermore, the assessment also requires the calculation of the average depth of the complex shaped defect (Step 1) and the calculation of the average depth of the idealised 'patch' for each given depth increment (Step 4).

See Section 4.5.2 for a discussion of the significance of correlated and uncorrelated measurements of a corrosion profile.

The implementation of the method for accounting for correlated and uncorrelated measurements when assessing complex shaped defects is described below. No additional probabilistic calibration has been carried out.

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

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

The acceptance equation in Step 2 requires the characteristic value of the relative average corrosion depth, defined as $(d_{ave}/t)^*$.

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

It can be shown that for fully correlated depth measurements:

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

and for uncorrelated depth measurements that:

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

where:

$E[X]$	expected value of random variable X
$\mathrm{StD}[X]$	standard deviation of random variable X
A	projected area of corrosion in the longitudinal plane through the wall thickness
N_m	number of depth measurements taken to define the profile of a complex shaped defect
d_{ave}	average depth of a complex shaped defect
l_{total}	total longitudinal length of a complex shaped defect

t	pipe wall thickness

STEP 4 - Calculate the average depth of an idealised 'patch' as follows:

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

The acceptance equation in Step 5 requires the characteristic value of the relative average corrosion depth of the patch, defined as $(d_{patch}/t)^*$.

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

As previously, it can be shown that for fully correlated depth measurements:

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

and for uncorrelated depth measurements that:

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

where:

A_{patch}	area of an idealised 'patch' in a complex shaped defect
N_m	number of depth measurements taken to define the profile of a complex shaped defect
d_{patch}	average depth of an idealised 'patch' in a complex shaped defect
l_{patch}	total longitudinal length of an idealised 'patch' in a complex shaped defect

The characteristic value of the relative effective corrosion depth (Step 11 and Step 12) is calculated as described in Section 4.5.2.

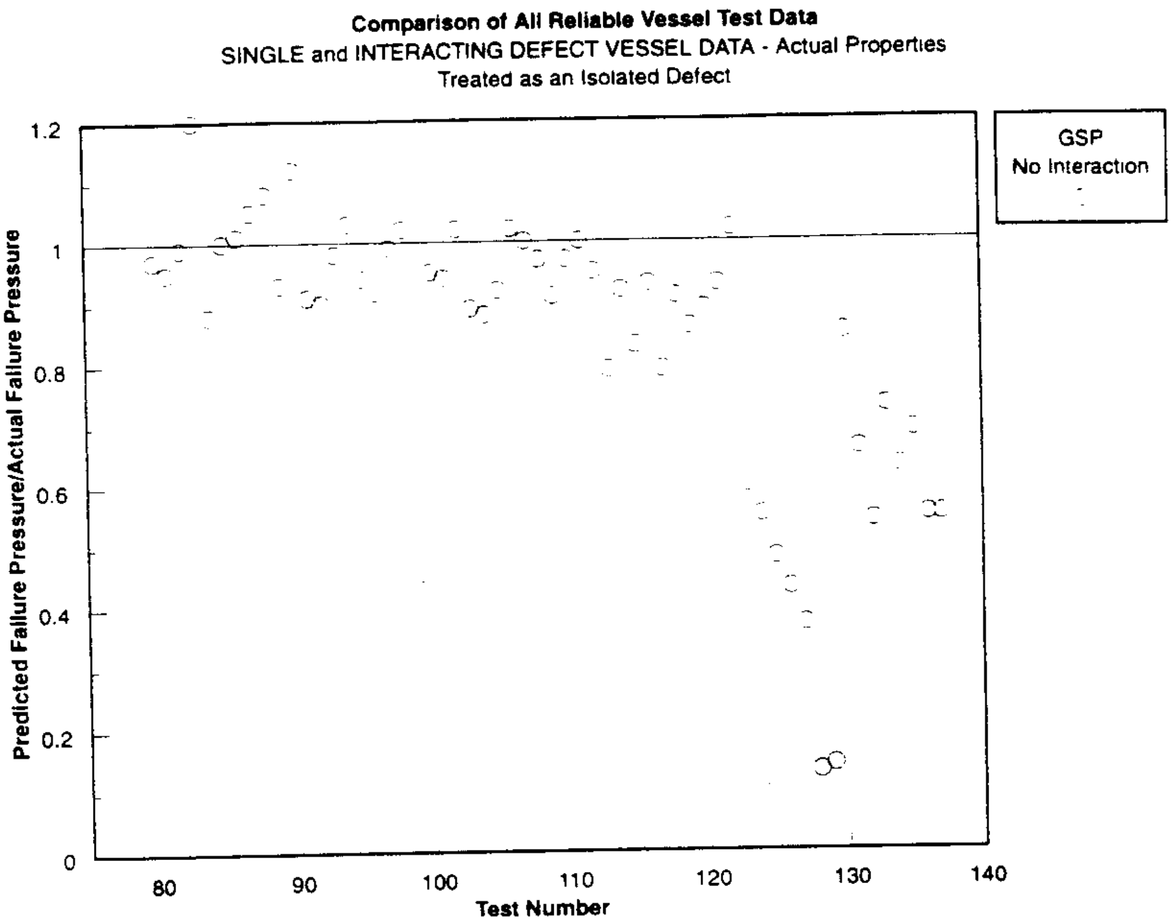

Figure 4.3 The Effect of Interaction - Defects Treated as Isolated Defects (Measured Properties)

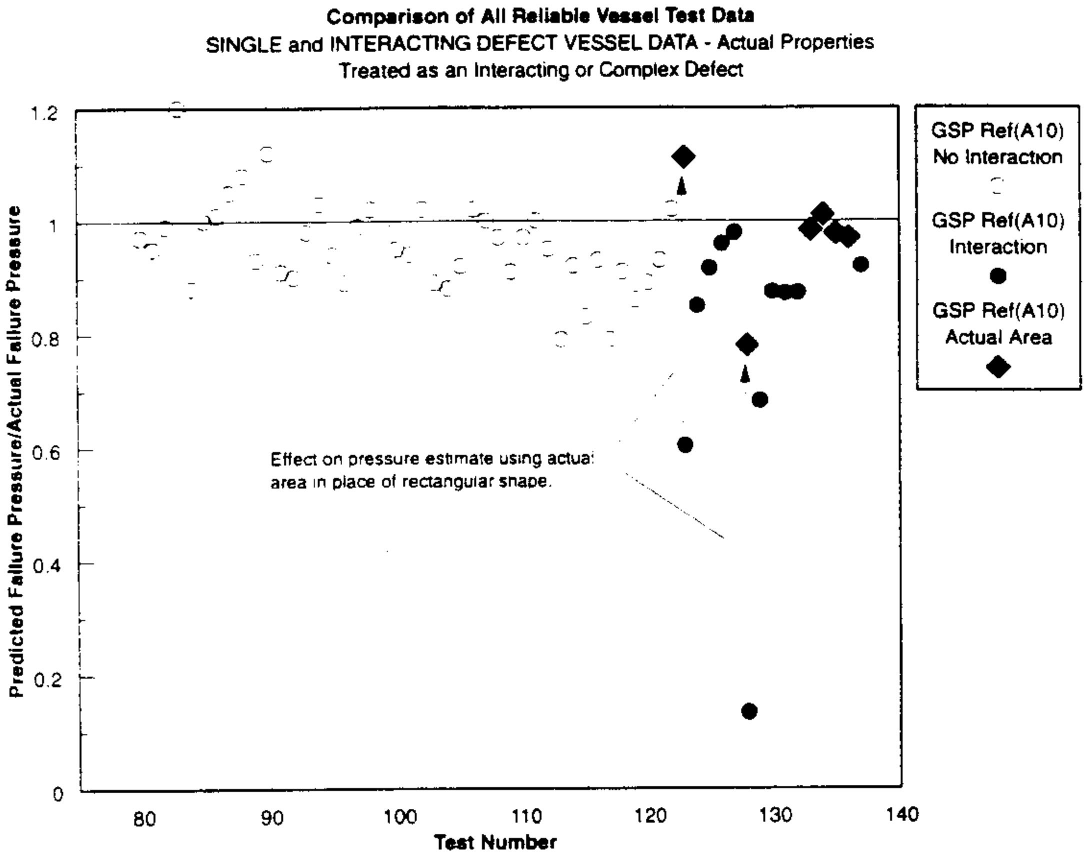

Figure 4.4 The Effect of Interaction - Defects Treated as Interacting or Complex Defects (Measured Properties)

5. COMBINED LOADING FOR LONGITUDINAL CORROSION

5.1 General

The proposed capacity and acceptance equations for burst of longitudinal corroded pipes exposed to combined internal pressure and external loading are defined in the following section.

It should be noted, however, that in the evaluation of the capacity of the corroded pipes for combined loading, other relevant failure modes must also be evaluated, see DNV Pipeline Rules 96 (DNV'96, 1996).

In the evaluation of the burst capacity of pipes with longitudinal corrosion for combined loading, only external longitudinal compression and external bending moment with compression in the corroded area has been considered. The proposed capacity and acceptance equations are only valid for longitudinal corrosion defects with a circumferential length less than the longitudinal length.

Corrosion in linepipe under combined loading should be assessed assuming load controlled conditions even if the response is displacement controlled. This will be conservative if the response is displacement controlled, but is recommended because it is not necessarily straightforward to determine whether the response will be load controlled or displacement controlled.

The burst capacity of the corroded pipe for these external load conditions has been derived based on a modelling of the allowable internal pressure and the longitudinal compressive stress level in the pipe, assuming that the failure surface follows the Tresca yield surface (i.e. linear in compression):

$$\left(\frac{P_H}{P_{H0}}\right)-\left(\frac{\sigma_{LP}}{\sigma_{LP0}}\right)=1 \qquad \text{... 5.1}$$

where P_H and σ_{LP} are the allowable combined internal pressure and longitudinal stress at the location of the corrosion, and P_{H0} and σ_{LP0} are the equivalent allowable limit values for internal pressure with no longitudinal stress and longitudinal stress with no internal pressure, respectively.

As defined here, σ_{LP} is the longitudinal stress level in the pipe at pressure level P_H (i.e. σ_{LP} includes the component of axial stress due to internal pressure), and σ_{LP} is negative for compressive loads.

5.2 Capacity Equation

In deriving the capacity equation, it is assumed that the limiting longitudinal stress for zero hoop stress is defined by the tensile strength and the remaining material cross section. The limiting values P_{H0} and σ_{LP0} are,

$$P_{HO} = \frac{2t\sigma_u}{(D-t)} \frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)} \text{, and}$$

$$\sigma_{LP0} = \sigma_u A_r$$

The capacity equation for the burst pressure capacity for combined internal pressure and longitudinal compression is defined as:

$$P_C = \frac{2t\sigma_u}{(D-t)} \frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)} \left(1+\frac{\sigma_{LP}}{\sigma_u}\frac{1}{A_r}\right) \qquad \text{... 5.2}$$

where:

σ_{LP} is the total longitudinal stress level in the pipe at pressure level P_C.

A_r is the ratio of the area of metal loss projected in the circumferential plane to the original area (the circumferential area reduction factor), and is defined as $A_r = \left(1-\frac{d}{t}\theta\right)$, and

θ is the ratio of the circumferential length of the corroded region to the nominal outside circumference of the pipe.

Alternatively, expressing the capacity equation in terms of the nominal longitudinal stress due to external loads σ_L (i.e. removing the component due to internal pressure) gives:

$$P_C = \frac{2t\sigma_u}{(D-t)} \frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)} \left[\frac{1+\frac{\sigma_L}{\sigma_u}\frac{1}{A_r}}{1-\frac{1}{2A_r}\frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)}} \right] \qquad \text{... 5.3}$$

5.3 Acceptance Equation

The acceptance equation for longitudinal corrosion under combined internal pressure and external loading (resulting in compressive longitudinal loading), is based upon the burst capacity formulation given above. The proposed acceptance equation has not been based on a probabilistic calibration for combined loading.

The acceptance equation for the burst pressure for combined internal pressure and longitudinal compression is defined as:

$$p_{corr.comp} = \gamma_m \frac{2tSMTS}{(D-t)} \frac{(1-\gamma_d (d/t)^*)}{\left(1-\frac{\gamma_d (d/t)^*}{Q}\right)} \left[\frac{1+\frac{\sigma_L}{\xi\, SMTS} \frac{1}{A_r}}{1-\frac{\gamma_m}{2\xi A_r} \frac{(1-\gamma_d (d/t)^*)}{\left(1-\frac{\gamma_d (d/t)^*}{Q}\right)}} \right] \qquad \ldots 5.4$$

where σ_L is the nominal longitudinal stress due to external loads.

The value of $p_{corr.comp}$ is defined depending on the desired safety level and the accuracy of the corrosion assessment.

γ_m, γ_d, ε_d and $(d/t)^*$ are defined in Section 4.4.

ξ is the usage factor for longitudinal stress (see Table 5.1).

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

Table 5.1 Usage Factors ξ

5.4 Comparison with laboratory tests

The capacity equation and the acceptance equation are compared with the full scale test results in this section.

A summary of the tests is given in Table 5.2. The dimensions given in the table are nominal values.

A normalised figure is given for each test (Figures 5.1 to 5.9, for tests 1 to 9 respectively). The x-axis is the normalised longitudinal pipe wall stress, including both the applied external load and the longitudinal stress due to internal pressure. The y-axis is the normalised hoop stress (the hoop stress has been calculated using the formula $\sigma_H = P(D-t)/(2t)$).

The loading path is given for each test. A dotted line is shown in each figure (corresponding to the equation $\sigma_H = 0.5\sigma_L$) representing the stresses due to internal pressure loading only. For comparison, the burst pressure predicted using the capacity equation for internal pressure loading only, is plotted for each test. Also shown in each figure is the Von Mises yield surface for the plain pipe (based on the uncorroded wall thickness). This curve shows when the loading would have reached a level such that the plain pipe would be predicted to be yielding.

The acceptance (or design) equation (Equation 5.4) for each test is presented in each figure. The acceptance equation shown in the figures corresponds to a 10^{-4} probability of failure and the assumptions that the dimensions of the corrosion defect are known exactly and that the additional material requirements are not fulfilled. The figures show that the acceptance equation gives a conservative prediction of the burst pressure of the corrosion defect for all of the tests.

Table 5.2 Overview of tests

Test no.	Nominal diameter (mm)	Nominal thickness (mm)	Grade	Defect depth (d/t)	Defect length	Defect width	Loading		
							int. press	/bending	/axial
1	324	10.3	X52	0.50	0.75 D	15 t	X		
2	324	10.3	X52	0.50	0.75 D	15 t	X	X	
3	324	10.3	X52	0.50	0.75 D	15 t	X	X	
4	324	10.3	X52	0.30	0.50 D	3 t	X	X	
5	324	10.3	X52	0.30	0.50 D	3 t	X		X
6	324	10.3	X52	0.30	0.50 D	3 t	X		X
7	324	10.3	X52	0.50	0.75 D	3 t	X		X
8	324	10.3	X52	0.50	0.75 D	3 t	X		
9	324	10.3	X52	0.70	0.75 D	3 t	X		X

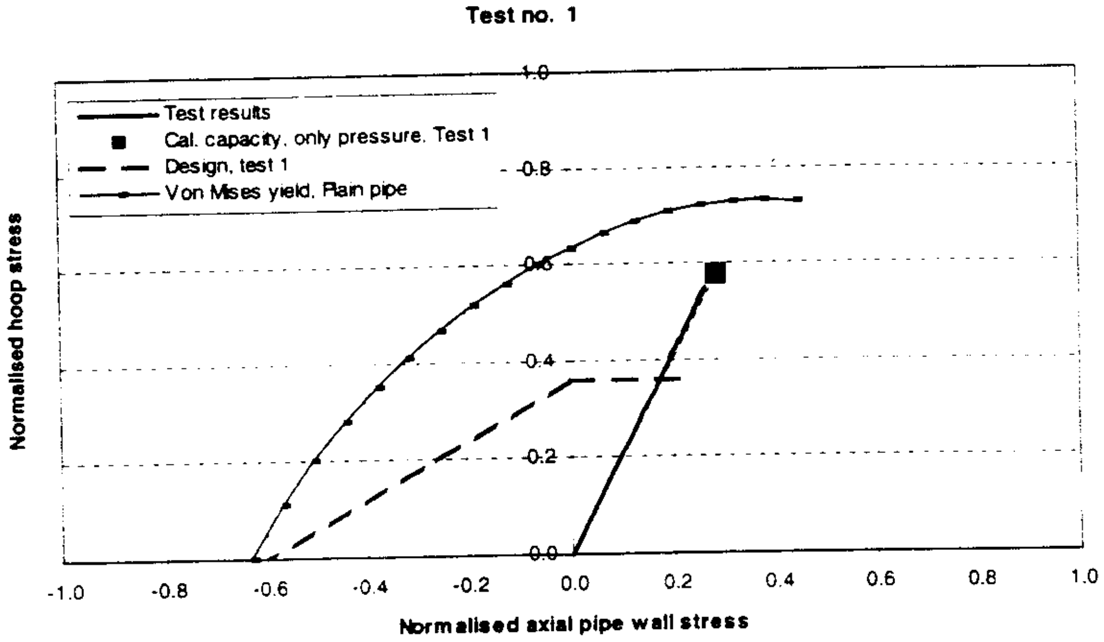

Figure 5.1 Test Number 1

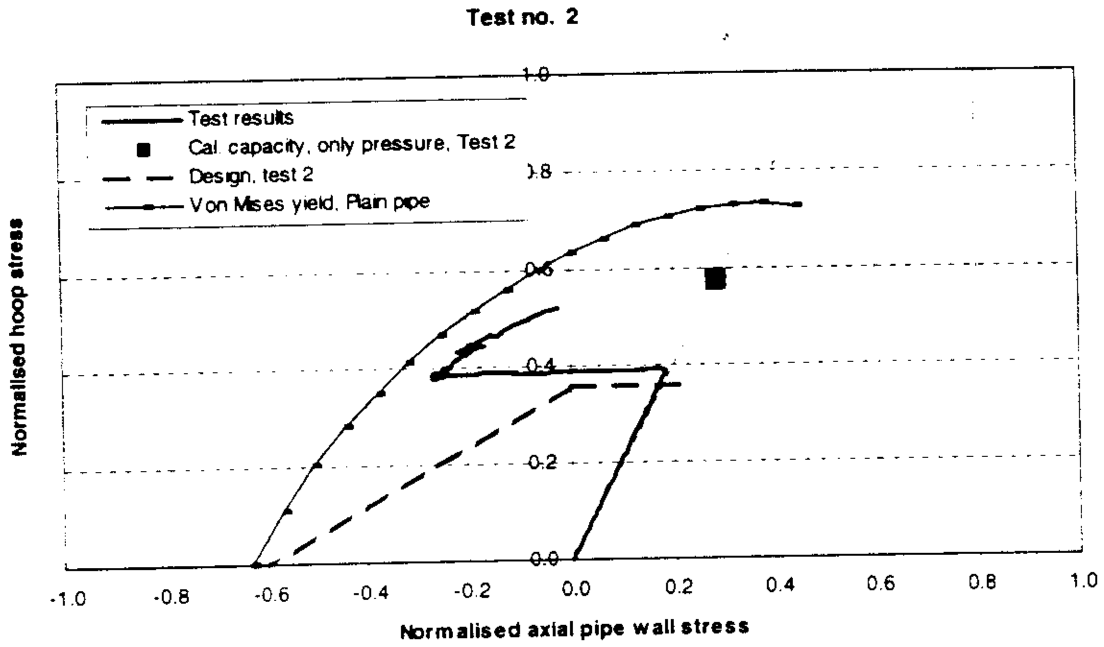

Figure 5.2 Test Number 2

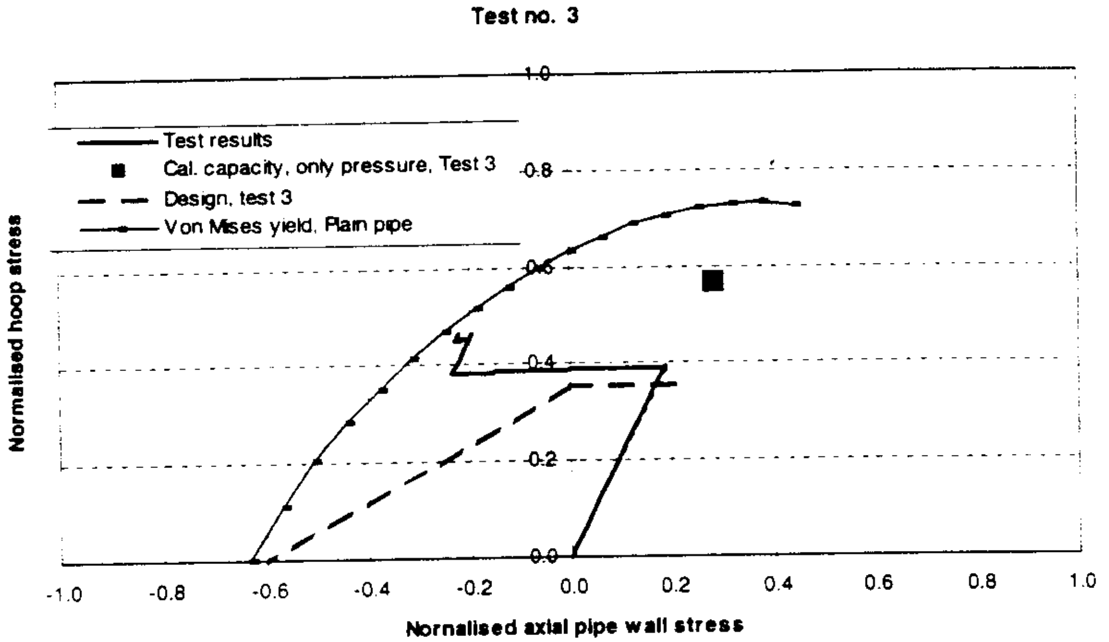

Figure 5.3 Test Number 3

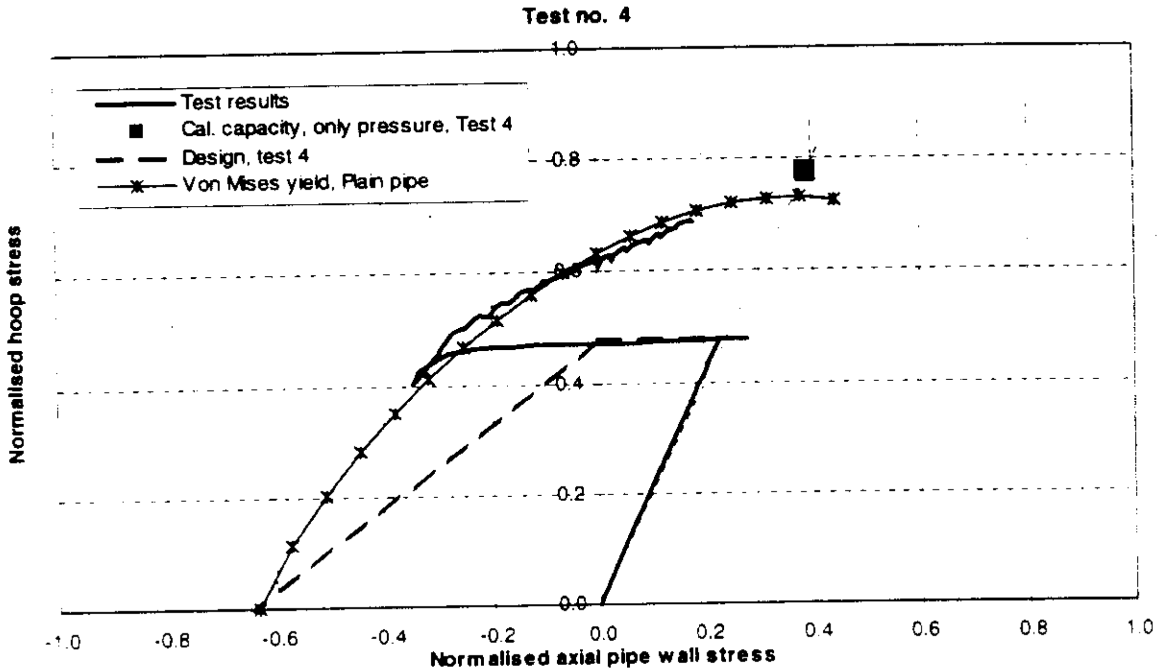

Figure 5.4 Test Number 4

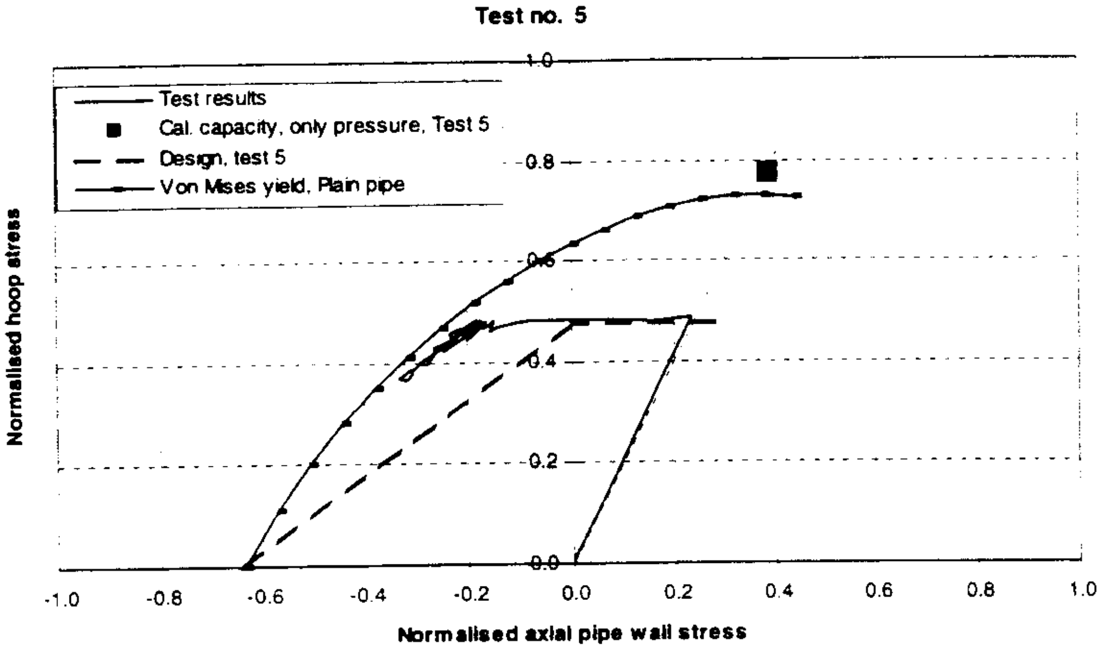

Figure 5.5 Test Number 5

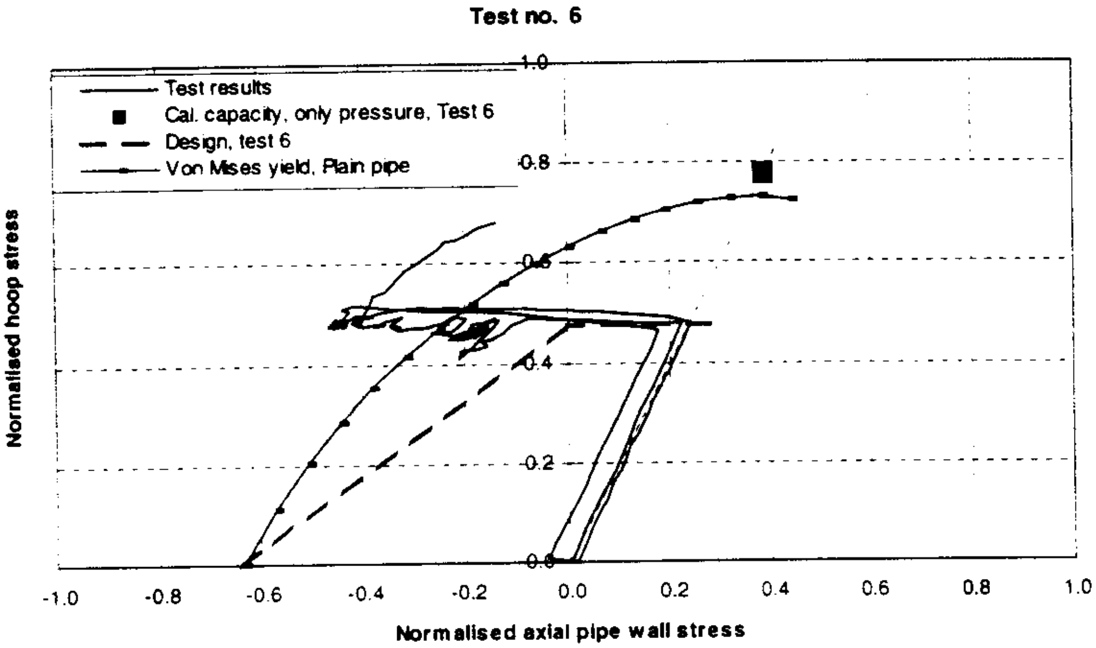

Figure 5.6 Test Number 6

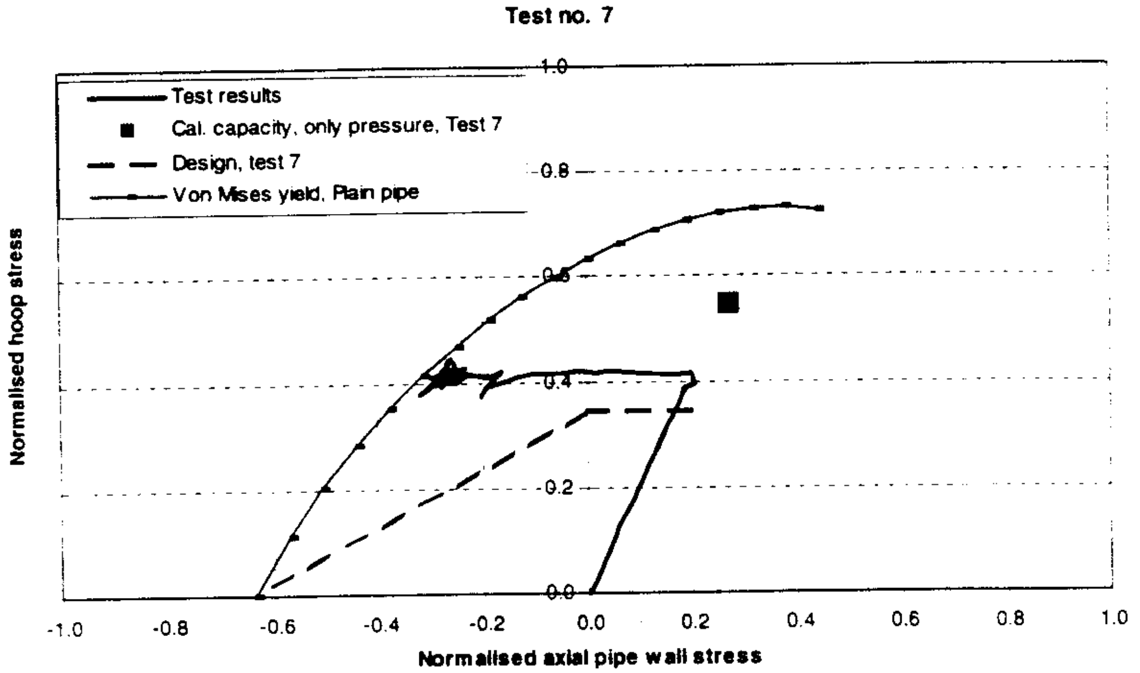

Figure 5.7 Test Number 7

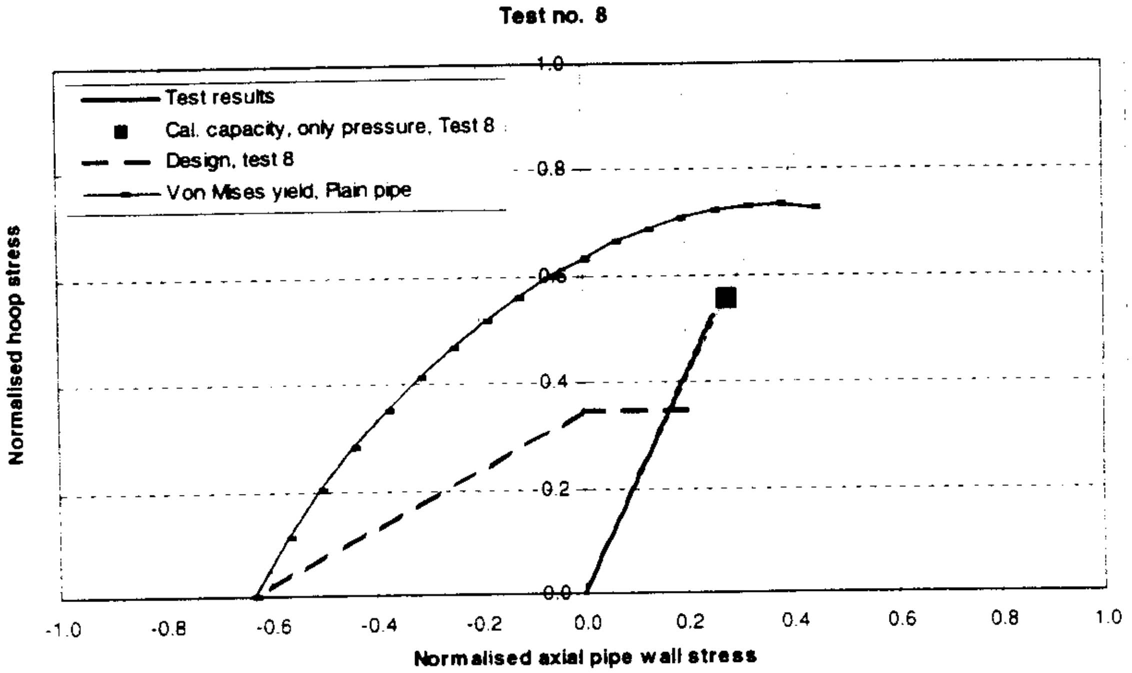

Figure 5.8 Test Number 8

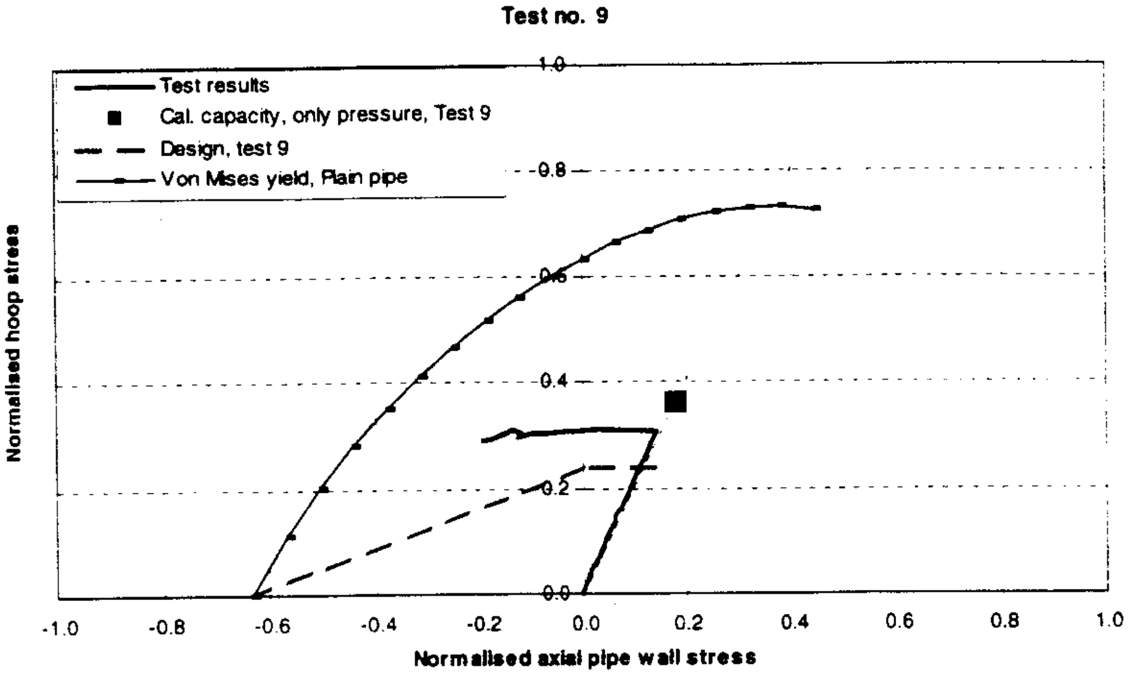

Figure 5.9 Test Number 9

6. COMBINED LOADING FOR CIRCUMFERENTIAL CORROSION

6.1 General

The proposed capacity and acceptance equations for the burst of pipes containing full circumferential corrosion subject to combined internal pressure and external loading are defined in the following section.

It should be noted, however, that in the evaluation of the capacity of circumferential corrosion under combined loading, other relevant failure modes must also be evaluated, see DNV Pipeline Rules 96 (DNV'96, 1996).

In the evaluation of the burst capacity of pipes with full circumferential corrosion under combined loading, only the cases of external longitudinal compression and external bending moment with compression in the corroded area have been considered. The proposed capacity and acceptance equations are only valid for full circumferential corrosion with a longitudinal length less than 1.5*t*.

Corrosion in linepipe under combined loading should be assessed assuming load controlled conditions even if the response is displacement controlled.

The burst capacity of circumferential corrosion for these external load conditions has been derived based on a modelling of the allowable internal pressure and the longitudinal compressive stress level in the pipe, assuming that the failure surface follows the Tresca yield surface:

$$\left(\frac{P_H}{P_{H0}}\right)-\left(\frac{\sigma_{LP}}{\sigma_{LP0}}\right)=1 \qquad \text{... 6.1}$$

where P_H and σ_{LP} are the allowable combined internal pressure and longitudinal stress at the location of the corrosion, and P_{H0} and σ_{LP0} are the equivalent allowable limit values for internal pressure with no longitudinal stress and longitudinal stress with no internal pressure, respectively.

The allowable internal pressure capacity is then defined as,

$$P_H = P_{H0}\left[\left(\frac{\sigma_{LP}}{\sigma_{LP0}}\right)+1\right] \qquad \text{... 6.2}$$

As defined here, σ_{LP} is the longitudinal stress level in the pipe at pressure level P_H (i.e. σ_{LP} includes the component of longitudinal stress due to internal pressure) and that σ_{LP} is negative for compressive loads.

6.2 Capacity Equation

In deriving the capacity equation, it is assumed that the limiting longitudinal stress for zero hoop stress is defined from the tensile strength and the remaining material cross section, and that fully circumferential corrosion with a longitudinal length of 1.5t or less does not reduce the burst capacity of the pipe for internal pressure loading only. Therefore, the limiting values P_{H0} and σ_{LP0} are,

$$P_{HO} = \frac{2t\sigma_u}{(D-t)}, \text{ and}$$

$$\sigma_{LP0} = \sigma_u A_r$$

The capacity equation for the burst pressure capacity for fully circumferential corrosion under combined internal pressure and axial compression is defined as.

$$P_C = \frac{2t\sigma_u}{(D-t)}\left(1+\frac{\sigma_{LP}}{\sigma_u}\frac{1}{A_r}\right) \qquad \text{... 6.3}$$

where:

σ_{LP} is the total longitudinal stress level in the pipe at pressure level P_C.

A_r is the ratio of the area of metal loss projected in the circumferential plane to the original area (the circumferential area reduction factor), and is defined as $A_r = \left(1-\frac{d}{t}\theta\right)$, and

θ is the ratio of the circumferential length of the corroded region to the nominal outside circumference of the pipe.

Alternatively, expressing the capacity equation in terms of the nominal longitudinal stress due to external loads σ_L (i.e. removing the component due to internal pressure) gives:

$$P_C = \frac{2t\sigma_u}{(D-t)}\left(\frac{1+\frac{\sigma_L}{\sigma_u}\frac{1}{A_r}}{1-\frac{1}{2}\frac{1}{A_r}}\right) \qquad \text{... 6.4}$$

An additional limit is imposed on the longitudinal stress. The longitudinal stress in the remaining ligament of the circumferential corrosion, is not to exceed the tensile strength, in tension or in compression.

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

6.3 Acceptance Equation

The acceptance equation for fully circumferential corrosion under combined internal pressure and longitudinal compression is based upon the burst capacity formulation given above. The proposed acceptance equation for fully circumferential corrosion has not been based on a probabilistic calibration for combined loading.

The acceptance equation is defined as,

$$p_{corr,circ} = \gamma_{mc} \frac{2tSMTS}{(D-t)} \left(\frac{1 + \frac{\sigma_L}{\xi\, SMTS} \frac{1}{A_r}}{1 - \frac{\gamma_{mc}}{2\,\xi} \frac{1}{A_r}} \right) \qquad \text{... 6.5}$$

where σ_L is the nominal longitudinal stress due to external loads.

The longitudinal stress in the remaining ligament of the circumferential corrosion, is not to exceed the specified minimum yield strength, in tension or in compression.

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

The acceptance equation was developed for a fully circumferential corrosion defect, and is valid for corrosion defects with a longitudinal length less than approximately 1.5t.

The acceptance equation is valid for internal pressure and external loads, limited to longitudinal and bending moments resulting in a compressive longitudinal stress component at the site of the corrosion defect.

The value of $p_{corr,circ}$ is defined depending on the desired safety level and the accuracy of the corrosion assessment.

γ_{mc} is the partial safety factor for the circumferential corrosion model prediction (see Table 6.1).

η is the partial safety factor for longitudinal stress for circumferential corrosion (see Table 6.2).

ξ is the usage factor for longitudinal stress (see Table 6.3).

Additional material requirements	Safety Class		
	Low	Normal	High
Not Fulfilled	$\gamma_{mc} = 0.81$	$\gamma_{mc} = 0.76$	$\gamma_{mc} = 0.71$
Fulfilled (see Section 4.3)	$\gamma_{mc} = 0.85$	$\gamma_{mc} = 0.80$	$\gamma_{mc} = 0.75$

Table 6.1 Partial Safety Factors γ_{mc}

Additional material requirements	Safety Class		
	Low	Normal	High
Not Fulfilled	$\eta = 0.96$	$\eta = 0.87$	$\eta = 0.77$
Fulfilled (see Section 4.3)	$\eta = 1.00$	$\eta = 0.90$	$\eta = 0.80$

Table 6.2 Partial Safety Factors η

Safety Class	Usage Factor ξ
Low	$\xi = 0.90$

Normal	$\xi = 0.85$
High	$\xi = 0.80$

Table 6.3 Usage Factors ξ

6.4 Comparison with laboratory tests

The capacity equation and the acceptance equation are compared with the full scale test results in this section.

A summary of the tests is given in Table 6.4. The dimensions given in the table are nominal values.

A normalised figure is given for each test (Figures 6.1 to 6.3, for tests 10 to 12 respectively). The x-axis is the normalised longitudinal pipe wall stress, including both the applied external load and the longitudinal stress due to internal pressure. The y-axis is the normalised hoop stress (the hoop stress has been calculated using the formula $\sigma_H = P(D-t)/(2t)$).

The loading path is given for each test. A dotted line is shown in each figure (corresponding to the equation $\sigma_H = 0.5\sigma_L$) representing the stresses due to internal pressure loading only. For comparison, the burst pressure of the fully circumferential corrosion defect, predicted using the capacity equation for internal pressure loading only, is plotted for each test. Also shown in each figure is the Von Mises yield surface for the plain pipe (based on the uncorroded wall thickness). This curve shows when the loading would have reached a level such that the plain pipe would be predicted to be yielding.

The acceptance (or design) equation (Equation 6.5) for each test is also presented in each figure. The acceptance equation shown in the figures corresponds to a 10^{-4} probability of failure and the assumptions that the dimensions of the corrosion defect are known exactly and that the additional material requirements are not fulfilled. In addition to the acceptance equation, also shown in each figure (as two vertical lines) is the limit on the longitudinal stress in the remaining ligament. The figures show that the acceptance equation gives a conservative prediction of the burst pressure of a fully circumferential corrosion defect for all of the tests.

Table 6.4 Overview of tests

Test no.	**Nominal diameter (mm)**	**Nominal thickness (mm)**	**Grade**	**Defect depth (d/t)**	**Defect length**	**Defect width**	**Loading**		
							int. press	**bending**	**axial**
10	324	10.3	X52	0.50	12 mm	circ.	X		X
11	324	10.3	X52	0.50	12 mm	circ.	X		X
12	324	10.3	X52	0.70	12 mm	circ.	X		X

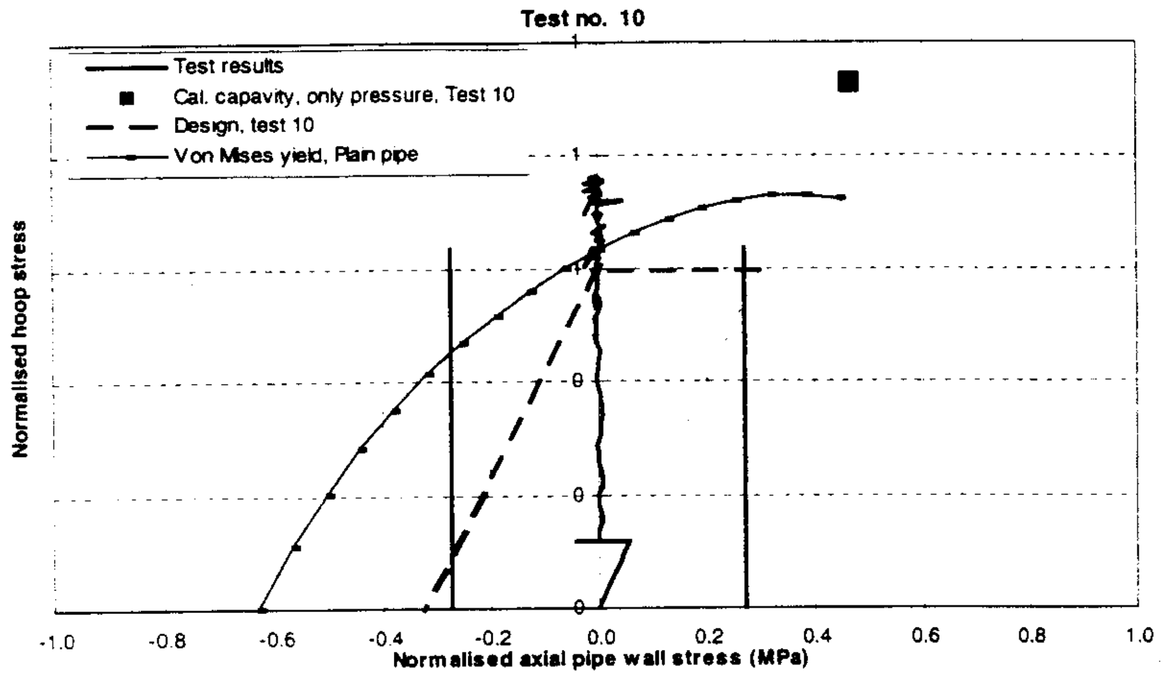

Figure 6.1 Test Number 10

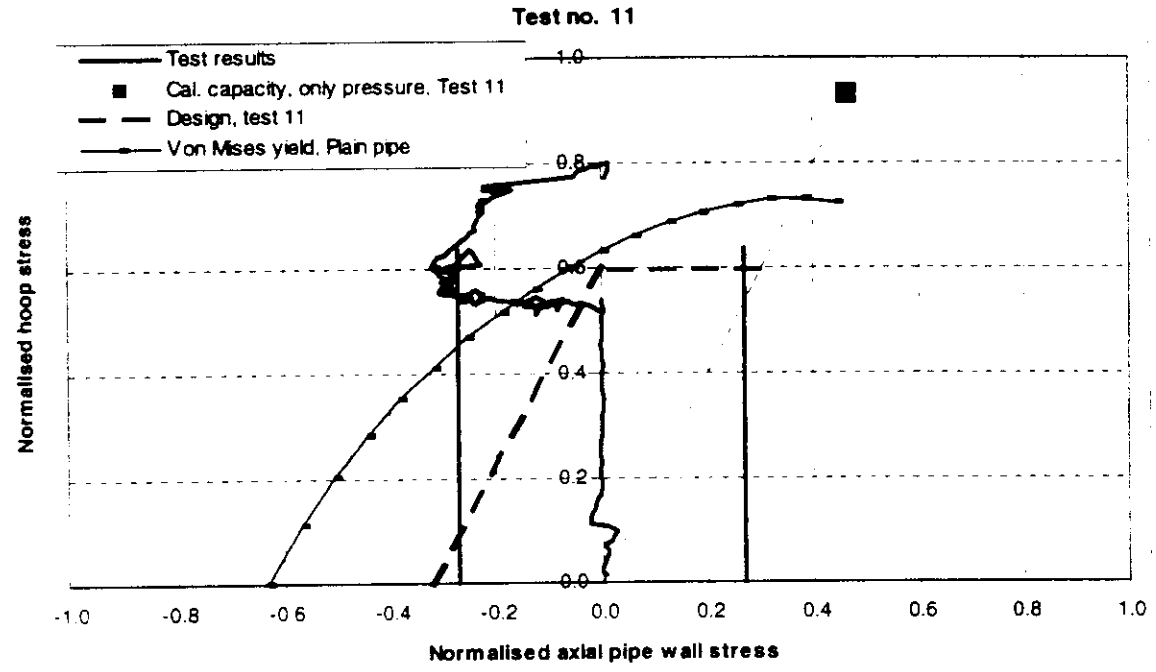

Figure 6.2 Test Number 11

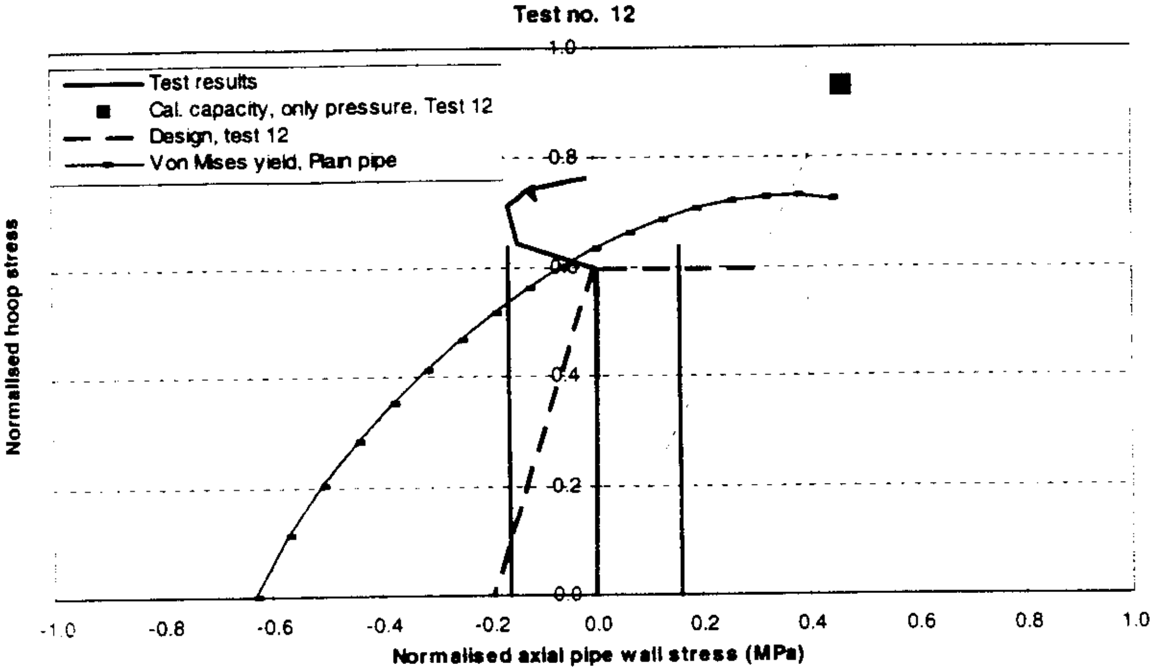

Figure 6.3 Test Number 12

7. ALTERNATIVE APPROACH FOR THE ASSESSMENT OF COMBINED LOADING FOR LONGITUDINAL AND CIRCUMFERENTIAL CORROSION

7.1 General

Internal pressure, and longitudinal and/or bending loads (tensile or compressive) will influence the failure mode of a corroded pipeline, as illustrated in Figure 7.1. The behaviour of corrosion defects under combined internal pressure and tensile longitudinal loads and/or bending loads, was outside the scope of the DNV and BG Technology projects. Therefore this loading combination has not been included as part of the main body of the guidance document.

Methods for assessing defects under combined internal pressure and bending loads, and/or tensile longitudinal loads, are recommended in other documents (e.g. PD6493:1991 and R6 (Milne et. al., 1987)). A method is described in this section for the assessment of single defects subject to internal pressure plus bending loads and/or tensile longitudinal loads. This is an extension of the methods described in Sections 5 and 6, which are limited to internal pressure and compressive longitudinal loads.

The correction for combined tensile longitudinal and/or bending loads is based upon a global plastic collapse solution for surface circumferential defects under bending and internal pressure loading. This plastic collapse solution has been validated for crack-like defects, but has not been validated for corrosion damage in large diameter pipeline materials (Miller, 1984). The LPC single defect failure equation is used to define the burst pressure under internal pressure loading.

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

7.2 Failure Mode

The method described below covers the effect of compressive axial stress on the reduction of the burst pressure of a single corrosion defect, and the influence of internal pressure on the failure of the defect due to external tensile longitudinal or bending loads. The method does not take account of the possible effect of the circumferential extent of the corrosion defect on the burst pressure under internal pressure loading only. Similarly, no account is taken of the possible effect of the longitudinal extent of the corrosion defect on the failure stress under longitudinal and/or bending loading only.

The failure surface is assumed to follow the Tresca yield surface, i.e. the failure surface is assumed to be linear in the compressive loading region. The failure surface is shown in Figure 7.1. The pressure and longitudinal stresses have been expressed in terms of the equivalent stresses in the full thickness pipe.

The failure mode (i.e. the influence of the external loading) depends on which failure boundary the load path meets. The solutions are intended to cover three modes of failure (see Figure 7.1):

1. Longitudinal failure due to internal pressure only.
2. Longitudinal failure at a reduced pressure due to longitudinal compressive stresses.
3. Circumferential failure due to the influence of combined internal pressure, and external longitudinal and/or bending loads.

Examination of the failure solutions for the various failure modes shows that they will overestimate the failure pressure if they are inappropriate to the particular load case. An alternative to estimating the load path is, therefore, to estimate the failure pressure due to each failure mode in turn, and select the minimum.

In addition to the above three failure modes, large compressive stresses may cause the pipe to buckle. The presence of corrosion may further increase the susceptibility to buckling. This limit state is not considered here.

7.3 External Loads

External loading on the line is defined in terms of the nominal elastic longitudinal and/or bending stresses produced by the external loading on the full thickness pipe. The nominal longitudinal elastic stresses in the pipe, based on the full pipe wall thickness, are assumed to be defined as follows:

$$\sigma_A = \frac{F_X}{\pi(D-t)t} \qquad \text{... 7.1}$$

$$\sigma_B = \frac{4M_X}{\pi(D-t)^2 t} \qquad \text{... 7.2}$$

The combined nominal longitudinal stresses is:

$$\sigma_L = \sigma_A + \sigma_B \qquad \text{... 7.3}$$

where:

F_X	external applied longitudinal force
M_X	external applied bending moment
σ_A	longitudinal stress due to external applied axial force, based on the full wall thickness
σ_B	longitudinal stress due to external applied bending moment, based on the full wall thickness
σ_L	combined nominal longitudinal stress due to external applied loads

It can be shown that if the external longitudinal and/or bending loads are within certain limits, then they will not be expected to affect the failure pressure of the corrosion defect. This is illustrated in Figure 7.2.

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

$$\sigma_1 < \sigma_L < \sigma_2 \qquad \text{... 7.4}$$

The value of these limits depends upon the limits for compressive and tensile longitudinal and/or bending loads only. For the method described below (see Section 7.4 and 7.5), it can be shown that the value of the limits on the external applied loads are:

$$\sigma_1 = -0.5\sigma_u \frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)} \qquad \text{... 7.5}$$

$$\sigma_2 = \sigma_u \left[K - 0.5\frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)}\right] \qquad \text{... 7.6}$$

where:

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

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

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

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

$$YT = \frac{\sigma_y}{\sigma_u}$$

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

7.4 Longitudinal Failure

A longitudinal failure is defined as when the pipe fails in a direction along its axis. This type of failure is typical of the failure generated by internal pressure in an end capped pressure vessel. The longitudinal failure pressure can be reduced by compressive stresses arising from bending and/or direct longitudinal compressive loads.

The failure pressure under internal pressure loading only (i.e. a longitudinal failure due to internal pressure only) is (from the LPC single defect failure equation):

$$P_{.} = \frac{2t\sigma_u}{(D-t)} \frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)} \qquad \text{... 7.7}$$

The limiting compressive longitudinal stress (σ_{LP0}), for zero hoop stress, is defined from the tensile strength and the remaining material cross section.

$$\sigma_{LP0} = \sigma_u A_r \qquad \text{... 7.8}$$

(It should be noted that these limits are identical to those described in Section 5.2.)

The failure surface is assumed to follow the Tresca yield surface. Therefore, the expression for the failure pressure due to internal pressure and compressive stresses (i.e. a longitudinal failure at a reduced pressure due to longitudinal compressive stresses) is:

$$P_{comp} = \frac{2t\sigma_u}{(D-t)} \frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tQ}\right)} H_1 \qquad \text{... 7.9}$$

where:

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

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

The influence of compressive loading is assessed in the H_1 term. This introduces the circumferential width of the corrosion and the nominal external longitudinal stresses. The circumferential width of the corrosion is expressed as the fraction of the circumference, θ, and the nominal external longitudinal stress, σ_L, is the stress produced by the external force or bending moment on the full thickness pipe.

The above equation is only valid if the load path keeps in the region of compressive longitudinal stresses before failure. If H_1 is less than unity then the failure pressure is reduced by the compressive external loads. If H_1 is greater than unity then the expression is not valid.

7.5 Circumferential Failure

A circumferential failure is where the failure propagates around the circumference, rather than along the axis. This type of failure is typical of the failure which would be expected from tensile longitudinal and/or bending forces acting on the pipeline alone, or from internal pressure on very deep and narrow circumferential corrosion where the axial load due to internal pressure dominates.

A global plastic collapse solution for surface circumferential defects under bending and internal pressure loading is used (Miller, 1984).

The failure pressure of the corrosion defect due to internal pressure and tensile longitudinal and/or bending loads can be calculated from the following equation:

... 7.10

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

where:

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

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

$$\sigma_F = \frac{\sigma_u + \sigma_y}{2}$$

$$YT = \frac{\sigma_y}{\sigma_u}$$

The σ_F term is a flow stress.

The factor H_2 is a function of the geometry and external stresses and accounts for the influence of the tensile longitudinal and/or bending loads. If H_2 is less than zero then it signifies that the external loads are large enough to break the line around the circumference without any internal pressure (for this failure mode, the significance of the internal pressure is only the longitudinal stress due to the internal pressure). If H_2 is greater than unity then the expression is not valid (the failure mode is not circumferential, but longitudinal).

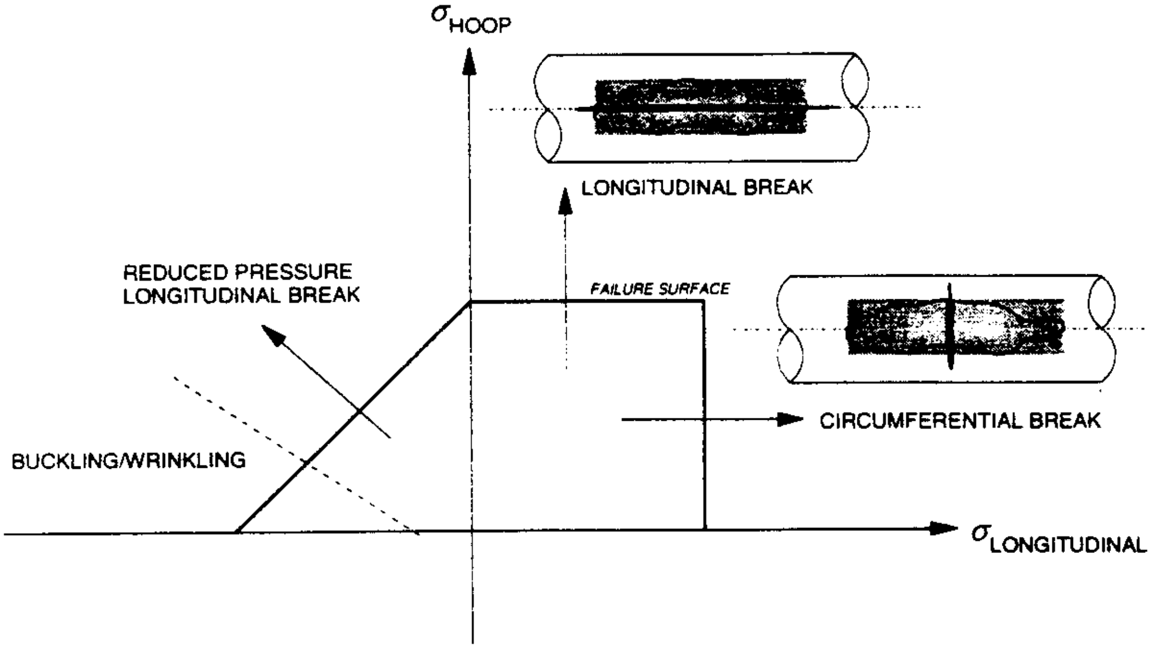

Figure 7.1 Influence of Applied Loads on the Failure Mode of a Corrosion Defect

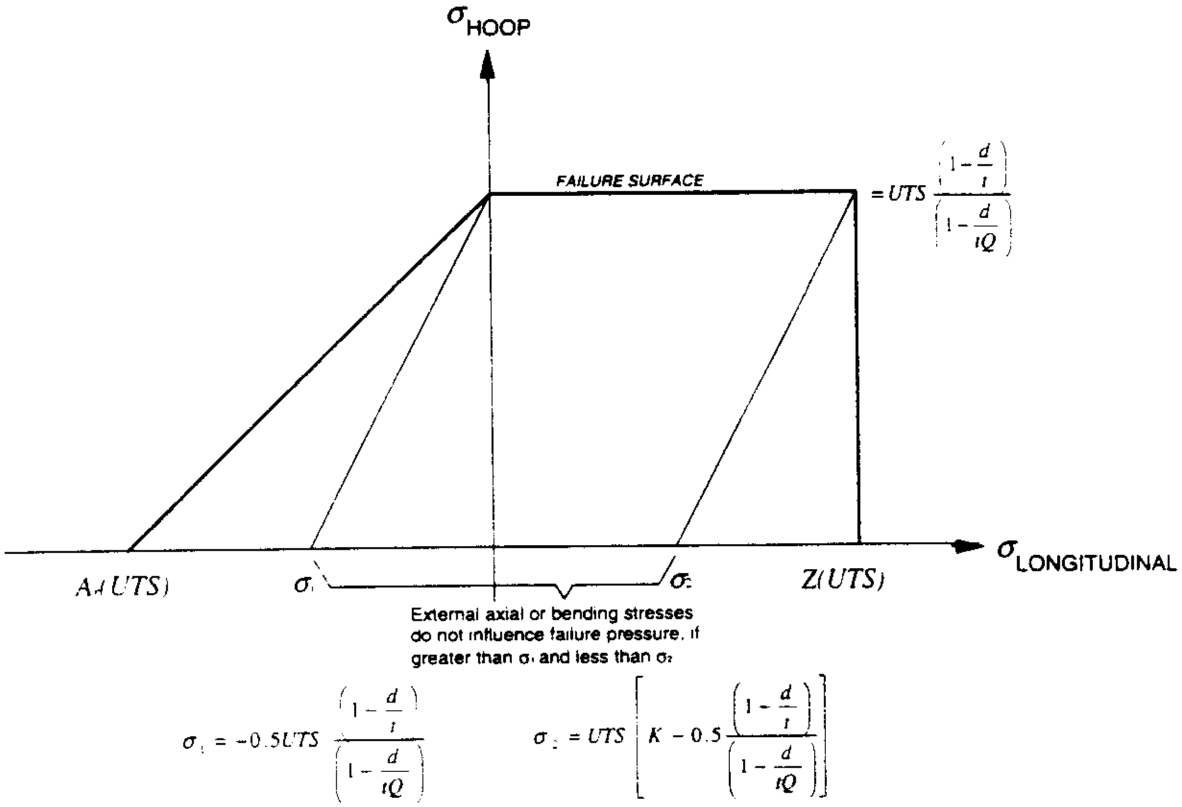

Figure 7.2 Range of Superimposed Longitudinal and/or Bending Loads which will not Influence the Failure Pressure

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