DNV

TECHNICAL REPORT

JOINT INDUSTRY PROJECT

RELIABILITY OF CORRODED PIPES
ASSESSMENT OF CAPACITY AND ACCEPTANCE CRITERIA

REPORT NO. 96-3394

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DET NORSKE VERITAS

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1 CONCLUSIVE SUMMARY

The objective of the JIP project "*Reliability of Corroded Pipes*" has been to provide capacity formulas and acceptance formulas with consistent reliability levels for corroded pipes.

The work includes a series of laboratory tests and a large number of finite element analyses of corroded pipes exposed to internal pressure, combined internal pressure and external axial loading, and combined internal pressure and external bending moment. Both longitudinal and circumferential corrosion have been considered.

The basis for the development of the capacity equation for longitudinal corrosion has been an extensive number of finite element analyses; a series of laboratory tests conducted within the research project and previously published test results on burst of corroded pipes.

The basis for the calibration of the acceptance equations for longitudinal corrosion has been the established capacity equation and bias factors accounting for the uncertainty associated with the burst capacities obtained from the finite element analyses and the laboratory tests. A procedure for probabilistic calibration has been defined, accounting for uncertainties associated with the corrosion assessment accuracy and the structural integrity of the corroded pipe. The partial safety factors in the acceptance equations are established using probabilistic calibration and full distribution structural reliability methods.

The partial safety factors are presented in tables for different levels of sizing accuracy of the inspection tool and defined target safety levels. Based on a measured corrosion attack (depth and length) the annual maximum allowable operating pressure is obtained for a specified inspection accuracy and selected safety level.

The established acceptance equations for longitudinal corrosion give a defined and consistent reliability level for variations in the corrosion depths and corrosion lengths. The influence of corrosion assessment accuracy is further accounted for in the proposed DNV acceptance equation, where increased assessment accuracy for the observed corrosion reduces the uncertainties and permits a higher allowable operating pressure.

The developed capacity and acceptance equations are defined for rectangular corrosion shapes only. A procedure for handling more general corrosion shapes based on a transformation of the corrosion shape into a series effective rectangular corrosion shapes is described.

Capacity and acceptance equations for circumferential corrosion have further been defined. However, these equations are not based on calibration.

The capacity and acceptance equations for both longitudinal and circumferential corrosion have been considered for combined loading, considering axial compression and bending with corrosion on the compression side.

The main results from the project are also presented in a separate project guideline.

2 INTRODUCTION

2.1 Motivation

A pipeline is a large financial asset for the pipeline operator and a safe operation of the pipeline is therefore of great concern. On the other hand, unnecessary repair and an over conservative operation of the pipeline may result in high costs and unexploded resource utilisation. As the pipelines are ageing and corrosion may develop, the economical consequences of reduced operation pressure, repairs, or replacements may become high.

Existing design codes for burst strength assessment of corroded pipes have a inconsistent safety level for varying degree of corrosion, which may result in both hazardous designs or possibly costly and unrequired requalification actions. Available acceptance equations for assessment of allowable operating pressures of degraded pipelines depending on the selected reliability level are therefore desirable.

When severe corrosion has been observed in a pipeline, the selection of required action to be carried out should be based on an overall assessment of the pipeline, where uncertainties associated with both the assessment of the degree of corrosion and the capacity evaluation should be considered. Repair or replacement of the pipeline should be avoided, or postponed in time, if this is possible within the safety requirements defined. Required actions should further also be initiated in order to maintain the integrity of the pipeline and to avoid an undesired risk exposure of the pipeline.

2.2 Background

The present Joint Industry Project "*Reliability of Corroded Pipes*" is a continuation of the project "*Residual Strength of Corroded and Dented Pipes*". The former project, Phase I, was started in 1993 and concluded at the end of 1995. The present project, Phase II, stared shortly after.

The Phase I of the project was sponsored by Statoil, Phillips, Brasoil (Petrobras), Mineral Management Services (MMS), Norwegian Petroleum Directorate (NPD), The Research Council of Norway (NFR), and Det Norske Veritas (DNV).

The Phase II of the project "*Reliability of Corroded Pipes*" is sponsored by Statoil, Amoco, Exxon, NPD, MMS and Brasoil (Petrobras).

The project scope of work has been modified during the course of the project to better utilise the funding. Especially, the work conducted by British Gas in a corresponding project has had an impact on the course of this project.

To avoid unnecessary overlapping, the initial scope was changed to covering the development of capacity and acceptance equations for combined internal pressure and external loading for both longitudinal corrosion and circumferential corrosion, where the acceptance equation for longitudinal corrosion was based on a probabilistic calibration. The basis for such a development was a series of finite element analysis and a reduced series of laboratory test compared to the initial scope.

British Gas had prior to the initiation of Phase II of the project performed several laboratory tests and finite element analyses for internal pressure only, accounting also for the interaction of separate pits and grooves. However, this work would not include a probabilistic calibration of an acceptance (design) equation. A merging of the outcome from the DNV and the British Gas projects would therefore be natural.

The advantage with a co-operation between the DNV and the British Gas projects would be that the obtained capacity and acceptance equations in the DNV project could be calibrated to a larger database. A set of common recommended capacity and acceptance design equations from the DNV and British Gas projects could then be proposed, which would also likely receive a higher recognition in the marked.

Such a co-operation could be initiated after the completion of both the DNV and the British Gas projects, by the development of a unified guideline for burst of corroded pipes.

2.3 Project Reports

The project concludes with the reports defined in Table 2-1.

Table 2-1 Overview of the project reports

DNV report no.	Title / Subject
96-3392	Reliability of Corroded Pipes / Finite Element Analyses
96-3393	Reliability of Corroded Pipes / Laboratory Burst Tests
96-3394	Reliability of Corroded Pipes / Assessment of Capacity and Acceptance Criteria
97-3358	Reliability of Corroded Pipes / Project Guideline

2.4 Participants and their Representatives

The following organisations participated in the project;

Participant	Representative	Telephone / Fax	
Minerals Management Service (MMS)	Wallace O. Adcox	Telephone Fax	(+1) 703 787 1354 (+1) 703 787 1010
Norwegian Petroleum Directorate (NPD)	Kjell A. Anfinsen	Telephone Fax	(+47) 51 87 62 26 (+47) 51 55 15 71
Den norske stats oljeselskap a.s.(Statoil)	Richard Verley	Telephone Fax	(+47) 73 58 41 85 (+47) 73 96 72 86
Amoco Norway Oil Company (Amoco)	Ole Jørgen Narvestad	Telephone Fax	(+47) 51 50 20 18 (+47) 51 50 22 18
Exxon Production Research Company (EPR)	Robert Appleby	Telephone Fax	(+1) 713 965 7193 (+1) 713 966 6423
Petrobras /CENPES/DIPREX	Adilson C. Benjamin	Telephone Fax	(+55) 21 598 6263 (+55) 21 598 6793

2.5 Conversion Factors

SI units are used in the report. The conversion factors between SI units and US units are;

From US units to SI units

Length:	1 in (inch)	=	25.40 mm
Mass	1 lb (pound)	=	0.4536 kg
Force	1 lbf (pound force)	=	4.448 N
	1 kip	=	4.448 kN
Stress (Pressure)	1 psi (lbf/in2)	=	0.006895 MPa (N/mm2)
	1 ksi (1000 psi)	=	6.895 Mpa

From SI units to U. S units

Length:	1 mm	=	0.03937 in
Mass	1 kg	=	2.205 lb (pound)
Force	1 N	=	0.2248 lbf (pound force)
	1 kN	=	0.2248 kip
Stress (Pressure)	1 Mpa	=	145.0 psi (lbf/in2)
	1 Mpa	=	0.1450 ksi

1 ksi = 1000 psi

10 bar = 1 MPa

2.6 Overview

2.6.1 Capacity Equation for Longitudinal Corrosion

The project "*Reliability of Corroded Pipes*" has focused on the development of probabilistic calibrated code design equations, hereby denoted acceptance equations, for burst of longitudinally corroded pipes. In order to obtain this, predictions for the burst capacity depending on the level of longitudinal corrosion must be available.

The calibration of the capacity equations for longitudinal corrosion was defined based on a calibration to the results of approximately 200 finite element analyses, where the following parameter range variations were covered:

• Degree of corrosion depth, d / t:	0.15, 0.3, 0.5, 0.7
• Degree of corrosion extension, $X = L / \sqrt{D \cdot t}$:	0.6 - 30.
• Tensile strength, σ_u:	520 - 727 MPa
• σ_y / σ_u relationship:	0.7, 0.8, 0.9

The acceptance equations for combined internal pressure and external loading were developed with basis in the acceptance equation for internal pressure. However, a calibration of the capacity equation was not carried our explicitly for the combined loading.

2.6.2 Acceptance Equation for Longitudinal Corrosion

The basis for the development of burst acceptance equations for longitudinally corroded pipes exposed to internal pressure have been:

- The use of nominal values for the pipe characteristics; the pipe thickness t and the outer diameter D.
- Characteristic description of the material quality; the actual yield strength σ_y and the actual tensile strength σ_u.
- An empirical description of the burst capacity defined based on a combination of numerical FE analyses and laboratory test results.
- Rectangular corrosion shapes.

The acceptance equations were defined for the following design conditions:

- Four levels of accuracy for the assessment of the corrosion depth:
  Exact, and 80% within ±5%, ±10% and ±20% of the thickness (CoV 0, ≈4%, ≈8%, ≈16%).
- Three levels of accuracy for the assessment of the corrosion length:

- Exact, std. 15 mm, and Std. 30 mm
- Three safety levels: $P_F = 10^{-2}, 10^{-3}, 10^{-4}$

The acceptance equations are based on the use of three partial safety factors with corresponding fractile levels for the characteristic parameters,

γ_M : Safety factor for capacity model uncertainty and determination of annual maximum operating pressure

γ_d Safety factor for corrosion depth assessment

ε_d : Fractile value for corrosion depth

γ_L Safety factor for corrosion length assessment

ε_L : Fractile value for corrosion length

Acceptance equations for combined internal pressure and external loading were developed with basis in the acceptance equation for internal pressure. However, a probabilistic calibration was not carried out explicitly for combined loading.

2.6.3 Circumferential Corrosion

Capacity equations for circumferential corrosion were defined with basis in the burst capacity for uncorroded pipes. No further calibration was carried out.

The acceptance equations for circumferential corrosion were defined with basis in the burst acceptance equation for uncorroded pipes. No further calibration was carried out

3 EXISTING CODES FOR CORRODED PIPES

The commonly applied B31G criterion for assessment of corroded pipes, ANSI/ASME B31G (ASME, 1991) was initially based on the NG-18 equation (Maxey et al. 1971) adjusted to account for available experimental data.

The NG-18 equation is defining the failure pressure as:

$$P = \frac{\sigma_{flow} \cdot 2 \cdot t}{D} \left[\frac{1 - \frac{A}{A_0}}{1 - \frac{A}{A_0} \cdot \frac{1}{M}} \right] \tag{3.1}$$

where

$$A_0 = d \cdot t$$

and

P	failure pressure
M	Folias bulging factor, accounting for effect of stress concentration at notch
σ_{flow}	flow stress
D	pipe outer diameter
A	projected corroded area
t	nominal pipe wall thickness
d	maximum corrosion depth

In the B31G criterion the projected corrosion area is assumed to be parabolic, and hence the projected corroded area is 2/3 $d \cdot t$. However, for long defects this assumption will obviously overpredict the capacity and a rectangular shape is introduced. The flow stress is limited to 10% higher than the specified minimum yield strength (SMYS).

The B31G burst equation is defining the safe maximum pressure P' as,

$$P' = 1.1 P \cdot \left[\frac{1 - \frac{2}{3} \cdot \frac{d}{t}}{1 - \frac{2}{3} \cdot \frac{d}{t} \cdot \frac{1}{M}} \right] \quad \text{for } \sqrt{0.8} \cdot X \le 4.0$$

$$P' = 1.1 P \cdot \left[1 - \frac{d}{t} \right] \quad \text{for } \sqrt{0.8} \cdot X > 4.0 \tag{3.2}$$

where P is the maximum allowable design pressure for uncorroded pipe

$$P = \frac{SMYS \cdot 2t}{D} \cdot F$$

$M = \sqrt{1 + 0.8 \cdot X^2}$ Folias bulging factor

$X = \frac{L}{\sqrt{D \cdot t}}$ Characteristic corrosion length

and F is the design factor, normally equal to 0.72.

The following restrictions apply:

- P' may not exceed P
- Corrosion above 80% of the wall thickness is not accepted.
- No further evaluation is needed for corrosion less than 10% of the wall thickness

In Figure 3-1, the safe maximum pressure level according to B31G is shown for corrosion depth of 0.3, 0.5 and 0.7 of the wall thickness.

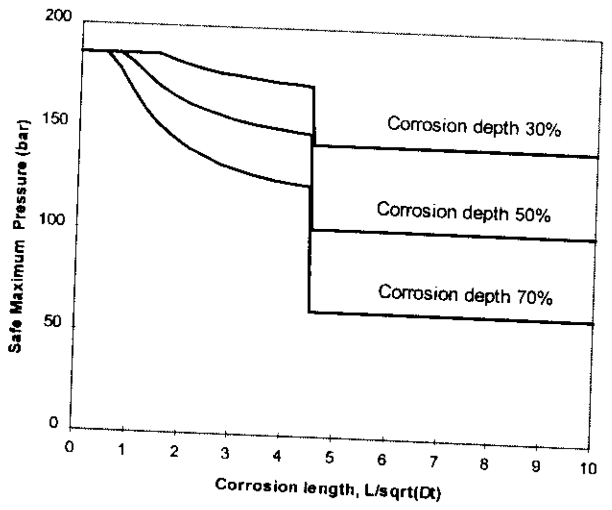


Figure 3-1 **Safe maximum pressure according to B31G.**

Several modifications have been proposed to improve the NG-18 / B31G criterion to better predict the actual failure pressure. These modifications have, however, mainly been based on modification changes of the equation parameters. An overview of some of these modifications to the flow stress, the bulging factor M and the procedure for estimating the projected corrosion area A is given below, (Denys, 1995).

Variations of proposed flow stress:

σ_{flow} = 1.1 SMYS

σ_{flow} = 1.15 SMYS

σ_{flow} = 0.5 (SMYS + SMTS)

σ_{flow} = SMYS + 69 MPa

σ_{flow} = a · SMTS, where $a = 0.90$, 1.0 or 1.1

where SMTS is the Specified Minimum Tensile Strength.

Variations of proposed projected corrosion area definition:

$A = d \cdot l$ (rectangular)

$A = 2/3\ d \cdot l$ (parabolic)

$A = 0.85\ d \cdot l$ (approx. average of rectangular and parabolic)

A = "exact" calculation (RSTRENG, Kiefner and Vieth, 1989)

Variations of proposed definition of bulging factor;

- Maxey et al (1971)

$$M = \sqrt{1 + 6.28 \cdot 10^{-1} \cdot X^2 - 3.38 \cdot 10^{-3} \cdot X^4}$$

- Kiefner (1974)

$$M = \sqrt{1 + 0.8 \cdot X^2}$$

- Kiefner and Vieth (1989)

$$M = \begin{cases} \sqrt{1 + 6.28 \cdot 10^{-1} \cdot X^2 - 3.38 \cdot 10^{-3} \cdot X^4} & X \leq \sqrt{50} \\ 3.3 + 3.2 \cdot 10^{-2} \cdot X^2 & X > \sqrt{50} \end{cases}$$

The drawback with modifying one or more parameters in the B31G equation in order to obtain a better adaptation to existing and newer results, is that it will most likely result in a negative effect for other design cases (geometries and corrosion configurations).

The inherent reliability level in B31G is very dependent on the length and shape of the corrosion. In Figure 3-2, the annual failure probability is estimated for rectangular corrosion shapes for different corrosion depths as function of the corrosion length applying B31G. Uncertainties in the corrosion sizing accuracy are included using the specification from the British Gas 020 system.

As can be seen in the figure, for a given measured corrosion depth the probability of failure varies significantly as function of the corrosion length. It should further be noticed the dramatic inconsistency in the reliability level for the different corrosion depths, e.g. for long corrosion the probability of failure is approximately 10^{-6} for $d/t = 0.3$, but higher than 10^{-2} for $d/t = 0.7$.

The inconsistent behaviour of the inherent reliability level for various corrosion depths and corrosion lengths in existing codes has been the incitement for development of new acceptance equations for corroded pipes in the present DNV joint industry research project *Reliability of Corroded Pipes*.

In order to obtain a better prediction for the burst capacity for all actual design combinations, a new burst capacity equation has been developed. The burst capacity equation is defined based on obtained data material on burst capacities and the use of advanced analysis procedures for transformation of these data to an applicable well behaving burst capacity formulations.

With basis in the defined burst capacity equation and an understanding of the uncertainties involved in the determination of the pressure exposure, the burst capacity and the level of corrosion, burst code equations with defined reliability levels for use in reassessment of corroded pipes have been developed.

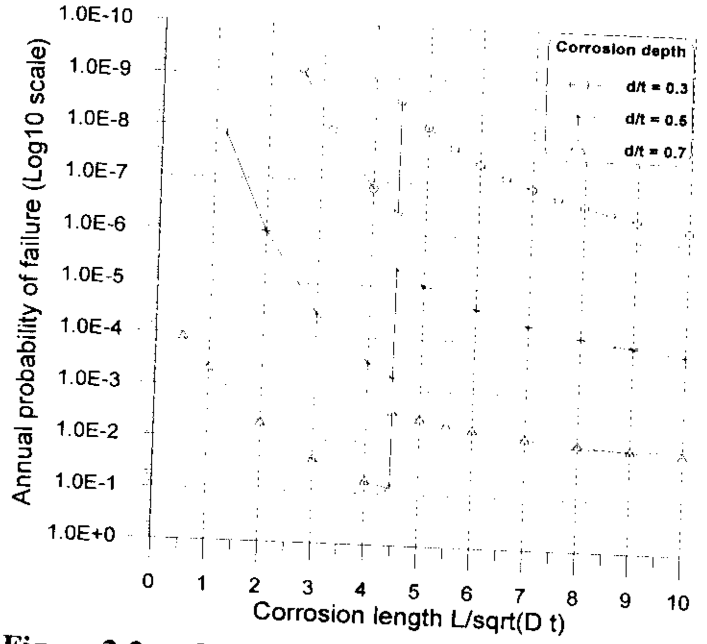


Figure 3-2 Inherent reliability level in B31G

4 BURST CAPACITY EQUATION FOR LONGITUDINAL CORROSION

4.1 General

To efficiently obtain reliable estimates for the burst capacities together with predictions of the influence of parameter variations, the expression for the burst capacity was estimated based on a combination of a large number of finite element analyses and a series of full-scale laboratory tests.

The finite element analyses were carried out using three-dimensional models with fully non-linear capabilities applying the program system ABAQUS, (Hibbitt, Karlsson and Sorensen, 1995). Approximately 200 analyses were carried in the establishment of the burst capacity equation, where variations in pipe geometry D/t, corrosion length, corrosion depth and material characteristics were intensively studied.

In addition to these parametric studies, the influence of various corrosion shapes, internal versus external corrosion, mesh density, solution strategy and 2D analyses for long corrosion were investigated. The failure criterion for the finite element analyses predicting the burst pressure was based on the work by British Gas (Fu and Kirkwood, 1995), and confirmed by laboratory tests. A more detailed description of the finite element analyses and the obtained numerical capacities for the various cases considered are given DNV *Reliability of Corroded Pipes* (1997b).

As the extent of available published burst data was insufficient for an improvement of the existing burst capacity equations for corroded pipes, an extensive laboratory test program was initiated in order to obtained more burst capacity data for corroded pipes, DNV *Reliability of Corroded Pipes* (1997a).

The laboratory tests carried out within the DNV project covered variations in the corrosion geometry as well as different combinations of internal pressure loading and external axial and bending loads, where a total of 12 tests were carried out.

The calibration of the expression for the burst capacity comprises both the results from the laboratory tests carried out within the project as well as available burst capacity results from the literature (Chouchaoui and Pick, 1992), (Coulson and Wolthingham, 1991).

4.2 Capacity Modelling

The expression for the burst capacity was established with basis in the initial form of the NG-18 and the B31G equations, both in order to obtain continuity with previous work in the field and as the form of these equation was found 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;

- Modelling of the ability of the defined burst capacity equation to represent the burst capacity obtained from the intensive 3D finite element analyses.

- 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:

$$P_{CAP} = X_{model} \cdot X_{FEA} \cdot P_{fit} \tag{4.3}$$

where

P_{fit} obtained burst capacity from capacity equation

P_{CAP} obtained burst capacity from laboratory tests

P_{FEA} obtained burst capacity from numerical analysis

The bias in the burst capacity expression capacity relative to numerical obtained capacity is then

$$X_{FEA} = \frac{P_{FEA}}{P_{fit}}$$

and the bias in the numerically estimated burst capacity relative to the obtained laboratory capacity is

$$X_{model} = \frac{P_{CAP}}{P_{FEA}}$$

The expression for the burst capacity equation is defined on the following form,

$$P_{fit} = P_0 \cdot \frac{1 - d_t}{1 - \frac{d_t}{M}} \cdot H \tag{4.4}$$

where P_0 is the reference pressure,

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

M accounts for finite corrosion length and the corrosion profile,

$$M = 1 + A \cdot X^B \cdot (1 - d_t)^C$$

$$X = L / \sqrt{D \cdot t}$$

$$d_t = \frac{d}{t}$$

H accounts for the relative influence of the yield strength - tensile strength ratio and the extent and shape of corrosion,

$$H = H_1 \cdot H_2$$

$$H_1 = g_1 + g_2\,r + g_3\,r^2 \quad ; \quad r = \frac{\sigma_y}{\sigma_u}$$

$$H_2 = 1 - e_1 X^{e_2} \cdot \left(1 - \frac{X}{e_3}\right)^{e_4} \cdot \left(1 + \frac{X}{e_3}\right) \cdot (d_t)^{e_5}$$

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, B, C, $g_{1\text{-}3}$ and $e_{1\text{-}5}$ were determined through a calibration of the burst capacity expression.

4.3 Calibration

The expression for the burst capacity equation was calibrated to the obtained capacities from the FE-analyses. The results from more than 200 finite element analyses were considered, covering the following parameter range variations;

• degree of corrosion depth, d/t :	0.15, 0.3, 0.5, 0.7
• degree of corrosion extension, $X = L/\sqrt{D \cdot t}$:	0.6 - 30.
• 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-analysis were, however, carried out with a wider corrosion path, $9t$ and $15t$, resulting in minor variations on the obtained burst pressure capacity.

The calibrated fit was obtained by minimising the following expression,

$$\min \sum_{i=1}^{N_{FEM}} \left(\frac{P_{FEM}(i) - P_{fit}(i)}{P_0(i)} \right)^{\lambda} \qquad \textbf{(4.5)}$$

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

The following results were obtained:

$$A = 0.090 \quad B = 1.8 \quad C = 0.14$$

$$g_1 = 1.25 \quad g_2 = -0.70 \quad g_3 = 0.70$$

$$e_1 = 0.10 \quad e_2 = 0.0 \quad e_3 = 10.0 \quad e_4 = 2.0 \quad e_5 = 0.14$$

4.4 Burst Capacity Equation

The proposed expression for the burst capacity expression P_{fil} is

$$P_{fil} = P_0 \cdot \frac{1 - d_t}{1 - \frac{d_t}{M}} \cdot H \tag{4.6}$$

where

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

and

$$M = 1 + 0.090 \cdot X^{1.8} \cdot \left(1 - d_t\right)^{0.14}$$

and

$$H = H_1 \cdot H_2$$

$$H_1 = 1.25 - 0.70 \cdot r + 0.70 \cdot r^2 \qquad ; r = \frac{\sigma_y}{\sigma_u}$$

$$H_2 = 1 - 0.10 \cdot (1 - u) \cdot (1 - u^2) \cdot \left(d_t\right)^{0.14} \qquad ; u = \begin{cases} \frac{X}{10.0} & ; X \le 10.0 \\ 1.0 & ; \text{otherwise} \end{cases}$$

$$d_t = \frac{d}{t}$$

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

4.5 Prediction Ability of Capacity Equation

The burst capacity equation predicts the obtained finite element results extremely well, resulting in an unbiased factor with Coefficient of Variation (CoV) of only 1.4% for X_{FEA}. In Figure 4-3 the relationship between the corresponding capacities for the burst capacity equations and the finite element analyses is presented for internal pressure loading.

The burst capacity equation was also compared with the obtained laboratory test results, DNV *Reliability of Corroded Pipes* (1997a) and available published test results. The number of test results to be compared with the burst capacity equation is, however, limited as most of the published tests in the literature lack information on critical parameters, e.g. the actual yield strength or the ultimate tensile strength.

The burst capacity equation is here compared with tests from the AGA database (Kiefner and Vieth, 1994) and other published test results (Chouchaoui and Pick, 1992), (Coulson and Wolthingham, 1991).

The comparison shows that the burst strength equation predicts the available laboratory capacities with good accuracy, resulting in an unbiased model uncertainty X_{model} with CoV of 4.0 %. This model uncertainty factor is, however, expected to be modified as more laboratory burst results become available. In Figure 4-4, the relationship between the corresponding capacities for the burst capacity equations and available burst capacities from laboratory tests is presented.

The predicted burst capacity, normalised with the tensile strength hoop pressure P_0, as function of the corrosion length is shown in Figure 4-5 for a yield strength - tensile strength ratio of 0.8.

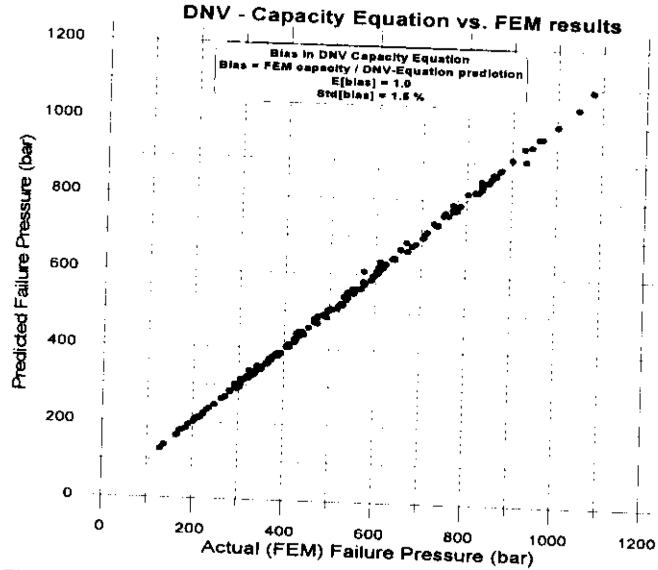


Figure 4-3 **Estimated burst capacity from DNV burst capacity equation versus finite element results.**

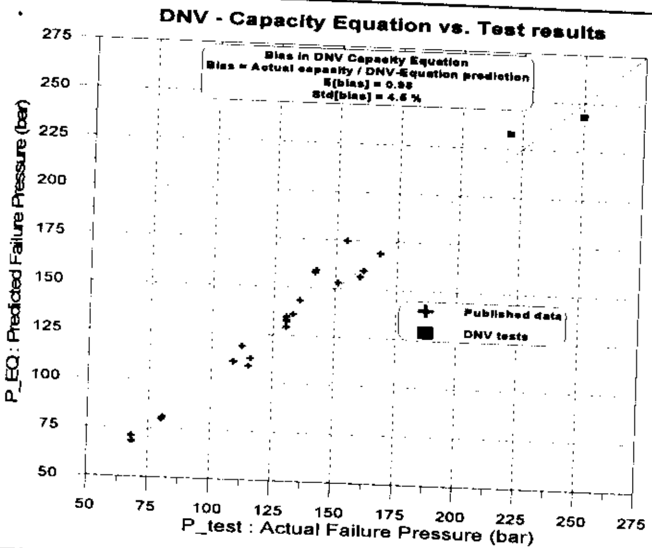


Figure 4-4 Estimated burst capacity from DNV burst capacity equation versus available laboratory test results.

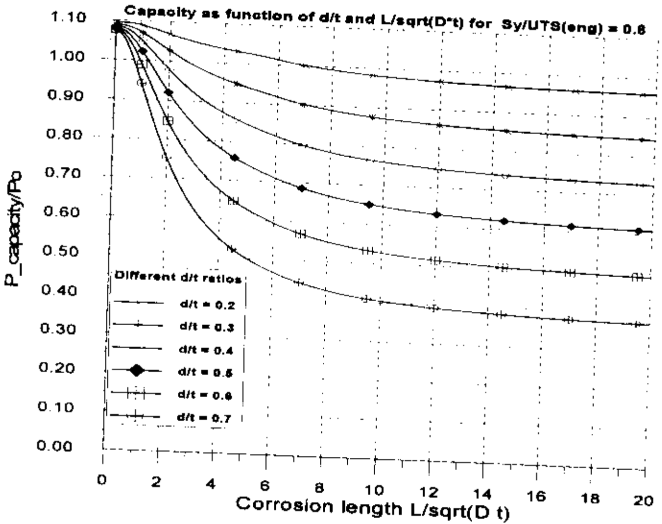


Figure 4-5 Burst capacity of depending on extent of corrosion.

4.6 Real Corrosion

The proposed capacity equation for longitudinal corrosion has been defined for rectangular corrosion shapes only. The possible influence of other corrosion shapes on the burst capacity was not investigated in detail in this study.

However, in order to determine the burst capacity for arbitrary corrosion shapes, an approach based on the *Effective Area* method described in (RSTRENG, Kiefner and Vieth 1989) could be applied.

For arbitrary corrosion shapes, the burst pressure capacity is estimated assuming a rectangular corrosion shape, where the expression for the burst pressure capacity defined in Equation (4.6) is applied. The corrosion length is, in order to cover different possible burst scenarios, defined for a series of different corrosion lengths, given as sub lengths of the total length of the corrosion attack. For each of the considered corrosion lengths, the corresponding corrosion depth to be applied is the average corrosion depth over the considered length of the corrosion attack.

The predicted burst pressure capacity for the corrosion attack is determined as the lowest obtained burst pressure capacity for the corrosion lengths considered.

The influence of possible interaction from multiple corrosion paths has not been considered in this study. However, multiple corrosion paths may, as a first approximation, be considered applying the same philosophy as for the *Effective Area* method, where rectangular corrosion shapes with varying corrosion lengths and corresponding corrosion depths defined as the average depth over the considered corrosion length.

5 ACCEPTANCE EQUATION FOR LONGITUDINAL CORROSION

5.1 General

The developed capacity equation predicts the burst capacity of corroded pipes with good accuracy for specified pipe material, pipe geometry, and corrosion characteristics as corrosion depth and length. However, some, or all, of these aspects are for a corroded pipe difficult to predict without some degree of uncertainty, resulting in a level of uncertainty on the estimated burst capacity.

In order to have a firm decision basis for the initiation of a possible action for observed corrosion, these uncertainties must rationally be accounted for in the prediction of the remaining burst capacity. A convenient way is to apply design codes, or acceptance equations, having a known safety level against burst and where the uncertainties are represented through characteristic values and partial safety factors.

However, the applicability of the design codes for corroded pipelines commonly used today are weakened due to an inconsistent reliability level against burst for various extent of corrosion and the assessment accuracy of the corrosion. It has, e.g. been observed that these codes are generally more conservative for ground corrosion than for deeper corrosion, see Figure 3-2.

In order to avoid unpredictability in the reliability level applying design codes, it is important that the codes reflect a known and consistent reliability against failure for all levels of corrosion. In the following, such an acceptance equation, or design code, is defined, where also the influence of various assessment accuracy for the corrosion level is accounted for.

5.2 Background

5.3 Calibration

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

As the different levels of uncertainty typically will have varying influence on the capacity estimate from design case to design case, the development of acceptance equations satisfying these reliability level requirements requires a detailed knowledge of the uncertainties involved and how these uncertainties affects 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 is typically uncertainties 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 (e.g. pipe thickness)
- the operation pressure (daily variations and efficiency of pressure control systems)
- 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 goodness of the applied inspection method and the type of corrosion considered. As these uncertainties to a large extend will affect the estimated burst capacity, the developed acceptance equations are defined for different levels of corrosion assessment accuracy.

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

5.3.1 Modelling

In order to embrace all realistic design scenarios, more than 200 design cases were considered in the calibration of the burst acceptance equation, covering the following variations:

- pipe material: X42 - X80
- measured corrosion depths: $d/t = 0.15 - 0.8$
- measured corrosion lengths: $L/\sqrt{D\cdot t} = 0.6 - 30$

As the assessment accuracy for the level of corrosion is affecting the estimated burst capacity of the pipeline, the acceptance equations where developed for different levels of assessment accuracy, both with respect to corrosion depth and corrosion length;

- Corrosion depth assessment accuracy;

  80% within 0, ±5% t, ±10% t, ±20% t (Std.: 0., ≈4% t, ≈8% t, ≈16% t)
- Corrosion length assessment accuracy;

  Std. = 0., 15.mm, 30.mm

The burst acceptance equations for corroded pipes were developed for three different annual failure probabilities (reliability indices),

- $P_F = 10^{-2}$ (β=2.32)
- $P_F = 10^{-3}$ (β=3.09)
- $P_F = 10^{-4}$ (β=3.71)

To assure a uniform reliability level for the different design scenarios at the defined reliability levels, the partial safety factors in the acceptance equation were determined applying a 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,

$$\min \sum_{i=1}^{N_{DES}} u\left(\beta_i - \beta_{target}\right) \tag{5.7}$$

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 established acceptance equation, the 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.

$$u(z) = \begin{cases} (\xi \cdot z)^{\lambda} & z \leq 0 \\ z^{\lambda} & z > 0 \end{cases} \tag{5.8}$$

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

The probabilistic evaluations were carried out using full distribution probabilistic methods and a first order approximation in the transformed standard normal space, applying 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 first order reliability method (FORM) in order to estimate the reliability level for any outcome of the design variables.

The response surface was computed based on combinations of the following parameters;

$E\left[\frac{P_{INT}}{P_0}\right]$: 0.10, 0.15, 0.20,..., 0.95

$E\left[\frac{d}{t}\right]$: 0.10, 0.20, 0.40, 0.60, 0.70

$E\left[\frac{L}{\sqrt{Dt}}\right]$: 1.0, 2.0, 3.0, 4.0, 6.0, 8.0, 12.0, 16.0, 20.0, 30.0

$CoV[L]$: 0.0, 0.05, 0.10, 0.20, 0.40

$E\left[\frac{\sigma_y}{\sigma_u}\right]$: 0.70, 0.80, 0.90

The response surface net was established for all combinations of the four defined corrosion depth assessment predictions and the three defined corrosion length assessment predictions.

5.3.2 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,

$$g = \frac{P_{CAP}}{E[P_0]} - \frac{P_{INT}}{E[P_0]} \tag{5.9}$$

where

$E[P_0]$: Normalising pressure, where $E[P_0] = \frac{2t}{D-t} \cdot E[\sigma_u]$ and $E[\sigma_u]$ is the mean value of the tensile strength for the pipe material.

P_{INT}: Annual largest internal pressure (difference)

P_{CAP}: Burst pressure capacity

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

$$\frac{P_{CAP}}{E[P_0]} = X_{model} \cdot X_{FEA} \cdot \frac{1 - d_t}{1 - \frac{d_t}{M}} \cdot H \cdot \frac{\sigma_u}{E[\sigma_u]} \tag{5.10}$$

where;

$$M = 1 + 0.090 \cdot X^{1.8} \cdot (1 - d_t)^{0.14}$$

$$H = H_1 \cdot H_2$$

$$H_1 = 1.25 - 0.7 \cdot r + 0.7 \cdot r^2 \qquad ; r = \frac{\sigma_y}{\sigma_u}$$

$$H_2 = 1 - 0.10 \cdot (1-u) \cdot (1-u^2) \cdot (d_t)^{0.14} \qquad ; u = \begin{cases} \frac{X}{10.0} & ; X \leq 10.0 \\ 1.0 & ; \text{otherwise} \end{cases}$$

$$d_t = \frac{d}{t}$$

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

and

X_{model}	Bias in FE results to laboratory tests.
X_{FEA}	Bias in empirical burst expression relative to FE results.
d	measured corrosion depth
L	measured corrosion length.
D	nominal outer diameter
t	nominal pipe thickness
σ_y	yield strength
σ_u	tensile strength

5.3.3 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 quality; 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 4, defined based on a combination of numerical FE analyses and laboratory test results.

Parameters for the modelling of the burst limit state equation is given in Table 5-2.

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	Corrosion depth	Normal	Measured value	Specified
X_{FEA}	Fit to FE results	Normal	1.0	1.4 %
X_{model}	Fit to laboratory results	Normal	1.0	4.0 %

Table 5-2 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 included in the stochastic modelling. However, probabilistic studies indicated that this uncertainty had a limited influence on the determination of annual maximum operating pressure for corroded pipes, and that a description of the pipe wall thickness by the nominal thickness was sufficient.

5.4 Burst Acceptance Equation

Based on the outcome of the probabilistic calibration, the proposed burst acceptance equation for the mean value of the annual maximum operating pressure is,

$$E[P_{INT}] = \gamma_M \cdot \frac{\mathrm{SMTS} \cdot 2t}{D-t} \cdot \frac{1-d_t^*}{1-\frac{d_t^*}{M^*}} \cdot H^* \tag{5.11}$$

where

$$H^* = 0.80 + 0.40 \cdot \frac{\mathrm{SMYS}}{\mathrm{SMTS}}$$

$$M^* = 1.0 + 0.12 \cdot X^{*1.6} \cdot \left(1-d_t^*\right)^{0.20}$$

$$d_t^* = \gamma_d \cdot \left(\frac{d_{\mathrm{meas}}}{t} + \varepsilon_d \cdot Std[d/t]\right)$$

$$X^* = \gamma_l \cdot \left(\frac{L_{\mathrm{meas}} + \varepsilon_L \cdot Std[L]}{\sqrt{Dt}}\right)$$

The subscript* defines the use of characteristic values and corresponding partial safety factors. The specified minimum yield strength (SMYS) and tensile strength (SMTS) are defined as (SUPERB project (Jiao et al 1995)),

$$\mathrm{SMYS} = E[\sigma_y] - 2 \cdot Std[\sigma_y]$$

$$\mathrm{SMTS} = E[\sigma_u] - 3 \cdot Std[\sigma_u]$$

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

γ_M : Model prediction

γ_d : Corrosion depth assessment

ε_d : Fractile level for corrosion depth

γ_L : Corrosion length assessment

ε_L : Fractile level for corrosion length

The partial safety factors and the corresponding fractile levels for the characteristic values are determined through probabilistic calibrations to the respective defined target reliability levels.

The calibrated values for the partial safety factors and the associated fractile levels for the characteristic values in the acceptance equation dependent on the desired reliability level and the assessment accuracy for the observed corrosion are given in Table 5-3, Table 5-4 and Table 5-5.

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

d^*;	measured corrosion depth (dependent on fractile level)
L^*;	measured corrosion length (dependent on fractile level)
D;	nominal outer diameter
t;	nominal pipe thickness
SMYS;	Specified Minimum Yield Strength
SMTS;	Specified Minimum Tensile Strength

5.5 Discussion

The partial safety factor for the modelling uncertainty accounts for the uncertainty associated with the goodness of the predicted bust capacity equation, the variation in the annual maximum operating pressure, and the variation in the tensile strength. The partial safety factors for the corrosion depth and length assessment accounts for the uncertainty associated with the prediction of the degree of corrosion from inspection results.

The proposed DNV acceptance equation may be applied to;

- Define allowable expected annual maximum operating pressure based on specified the corrosion assessment accuracy and the selected reliability level for the pipeline,
- Define the maximum allowable level of corrosion based on specified expected annual maximum operating pressure, corrosion assessment accuracy and selected reliability level of the pipeline

The corrosion assessment accuracy will depend on the type and quality of the inspection carried out on the pipeline. The variation in the assessment accuracy is reflected in the acceptance equation through the choice of partial safety factors, where an increased assessment accuracy results in the use of lower safety factors values for γ_d and γ_L. An increased effort to reduce the assessment uncertainties will then result in a higher allowable annual maximum operating pressure for observed corrosion.

Dependent on the required reliability level of the pipeline, typically defined based on the estimated consequence of a possible burst failure, different selections of partial safety factors are made. An increased reliability level results in a stricter set of partial safety factors and thereby a reduction in the annual maximum operating pressure.

The safety factors and characteristic values for the uncertain variables in the acceptance equations are carefully defined such that the code reflects a uniform reliability level over the range of possible corrosion shapes.

In Figure 5-6, the mean value of the annual maximum operating pressure based on the proposed DNV acceptance equation is compared with B31G and NG18 (both with safety factor F=0.8) for a corrosion depth assessment of 30% of the thickness (reported 30% corrosion depth). The DNV acceptance equation is here based on a typical estimate for the corrosion depth assessment accuracy of 80% probability within ±10% of the pipe thickness, while B31G and NG18 do not define any accuracy for the corrosion assessment uncertainty.

For comparison purposes, only the internal pressure loads are here accounted for, assuming no possible influence from additional axial or bending loads on the pipe. The proposed DNV pressure acceptance level is shown for three annual failure probability levels, 10^{-2}, 10^{-3} and 10^{-4}.

It is observed that for the present example, the B31G gives an overall conservative estimate for the annual maximum operating pressure. This is also the case for no corrosion, where the allowable operating pressure is less in the ASME code compared to the DNV Pipeline Rules 96 (DNV'96, 1996). The horizontal curve in the figure defines the maximum annual operating pressure for uncorroded pipes from DNV'96, accounting for scale effects. An estimated allowable annual operating pressure above this pressure limit is therefore not applicable.

For corroded pipes, the influence of scale effects on the estimated burst probability is omitted in the evaluation of the allowable operating pressure, as the corrosion defect considered typically is the largest of the observed corrosion paths and thereby reflects the weakest burst capacity point along the pipeline.

In Figure 5-7, the mean values of the annual maximum operating pressures for 50% corrosion depth according to the proposed DNV burst acceptance equation, B31G and NG18 are presented. It is observed that for this more extensive corrosion, the degree of conservatism within the existing codes is not as significant as for 30% corrosion depth and is highly dependent on the length of the corrosion.

In Figure 5-8, the mean values of the annual maximum operating pressures for 70% corrosion depth is given. The figure shows that for deep corrosion B31G is unconservative for both short and long corrosion lengths with respect to a failure probability level of 10^{-3} and 10^{-4}.

The effect of the inspection accuracy on the allowable operating pressure using the proposed DNV acceptance equation is shown in Figure 5-9, Figure 5-10 and Figure 5-11 for an annual failure probability of 10^{-4}. The figures demonstrate the importance of specifying the assessment accuracy of the observed corrosion in the determination of the allowable operating pressure, and highlight the necessity of including the quality of the inspections in the formulation of any acceptance equation for corroded pipelines.

In the proposed DNV acceptance equations, four levels of sizing accuracy of observed corrosion depth are considered;

- The common accuracy of intelligent pigging:	(80% within ±20% *t*)
- The latest accuracy of intelligent pigging:	(80% within ±10% *t*)

- The predicted future accuracy of intelligent pigging: (80% within ±5% t)
- Exactly known corrosion

As can be seen in Figure 5-9, Figure 5-10 and Figure 5-11, by increasing the inspection accuracy, unnecessary repairs, operating pressure reductions or shutdowns can be avoided. The figures also show that B31G is rather conservative for shallow corrosion depths, but becomes unconservative for moderate and deep corrosion having a lower assessment quality on the inspection accuracy.

The estimated annual failure probability applying the B31G code and the proposed DNV acceptance equation are shown in Figure 5-12 as a function of the corrosion length for different corrosion depths. For the DNV acceptance equation, partial safety factors corresponding to an annual failure probability of 10^{-4} and an exact corrosion assessment are applied. The figure presents thereby the inherent reliability level in both the DNV acceptance equation and the B31G code.

It is observed that the DNV acceptance equation gives a consistent probability for failure for various corrosion depths and corrosion length, while B31G varies dramatically, both with respect to the corrosion depth and the corrosion length. The inconsistency in the estimated reliability level for B31G, dependent on the level of corrosion, makes it therefore difficult to determine the inherent reliability level obtained applying this code in an evaluation of observed corrosion.

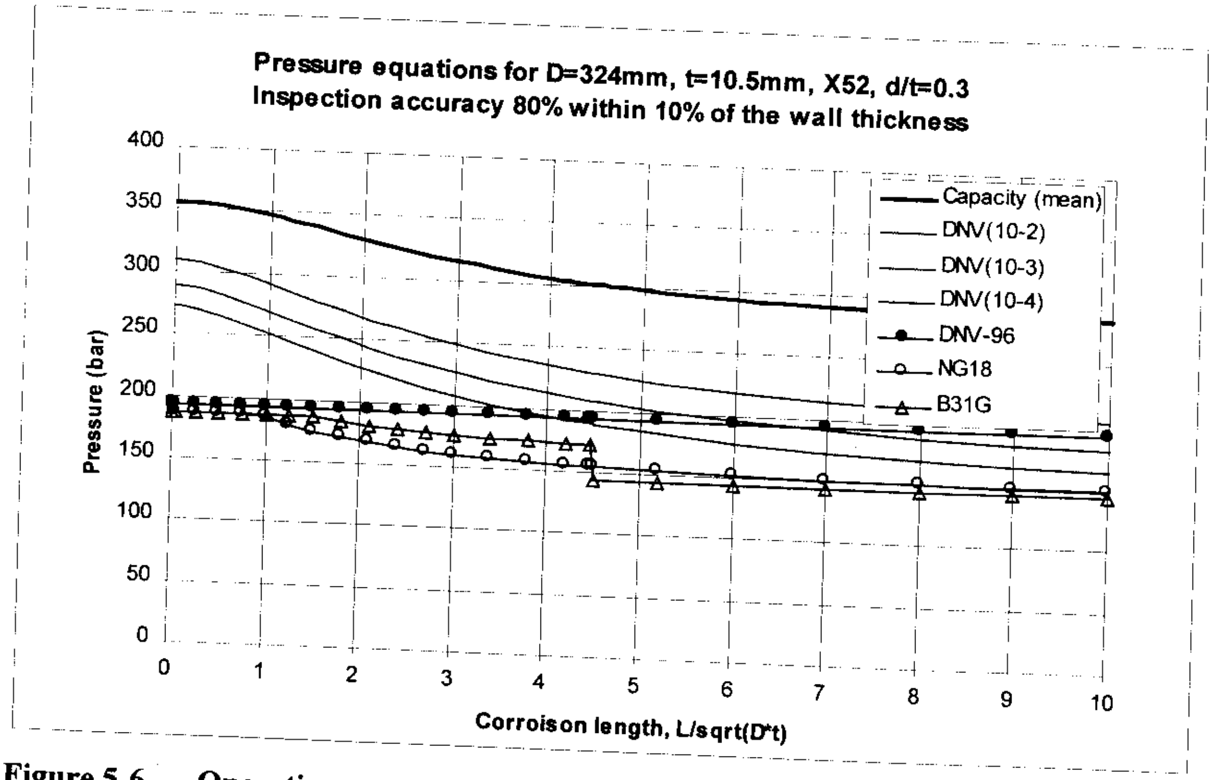


Figure 5-6 **Operating pressure for 30% depth corrosion.**

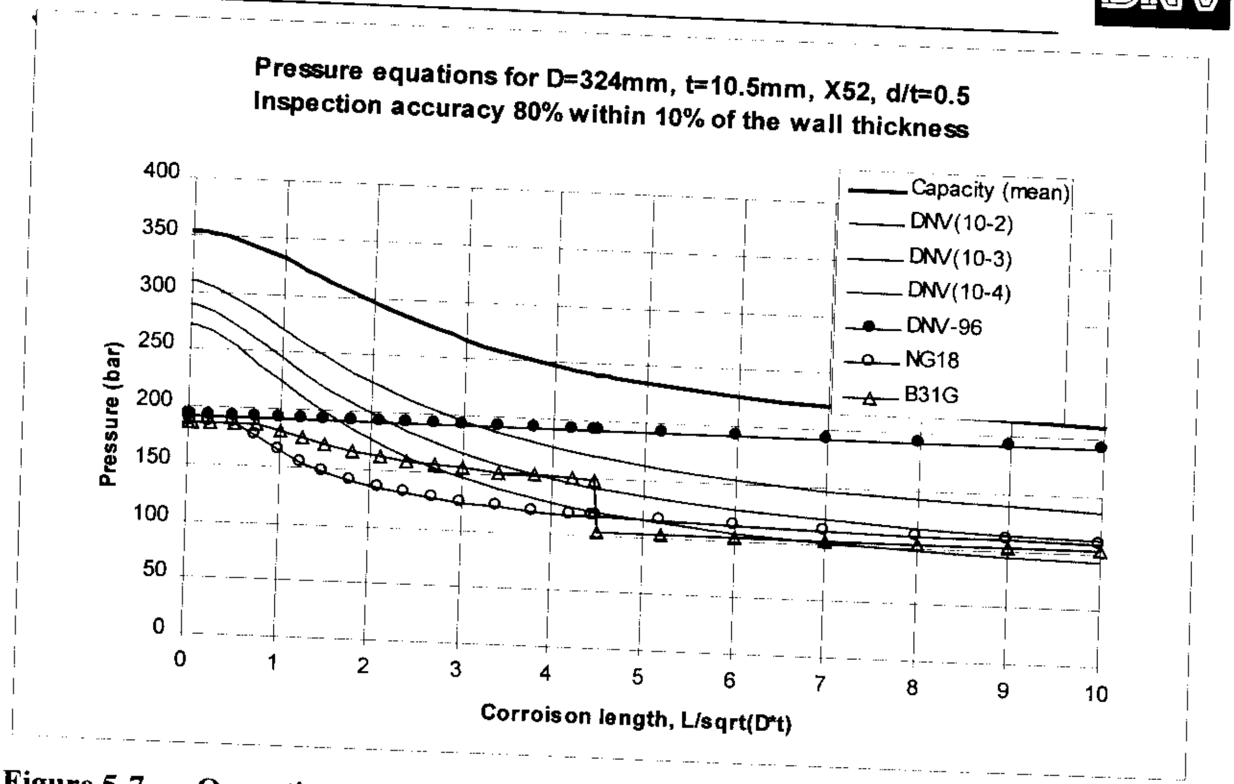


Figure 5-7 Operating pressure for 50% depth corrosion.

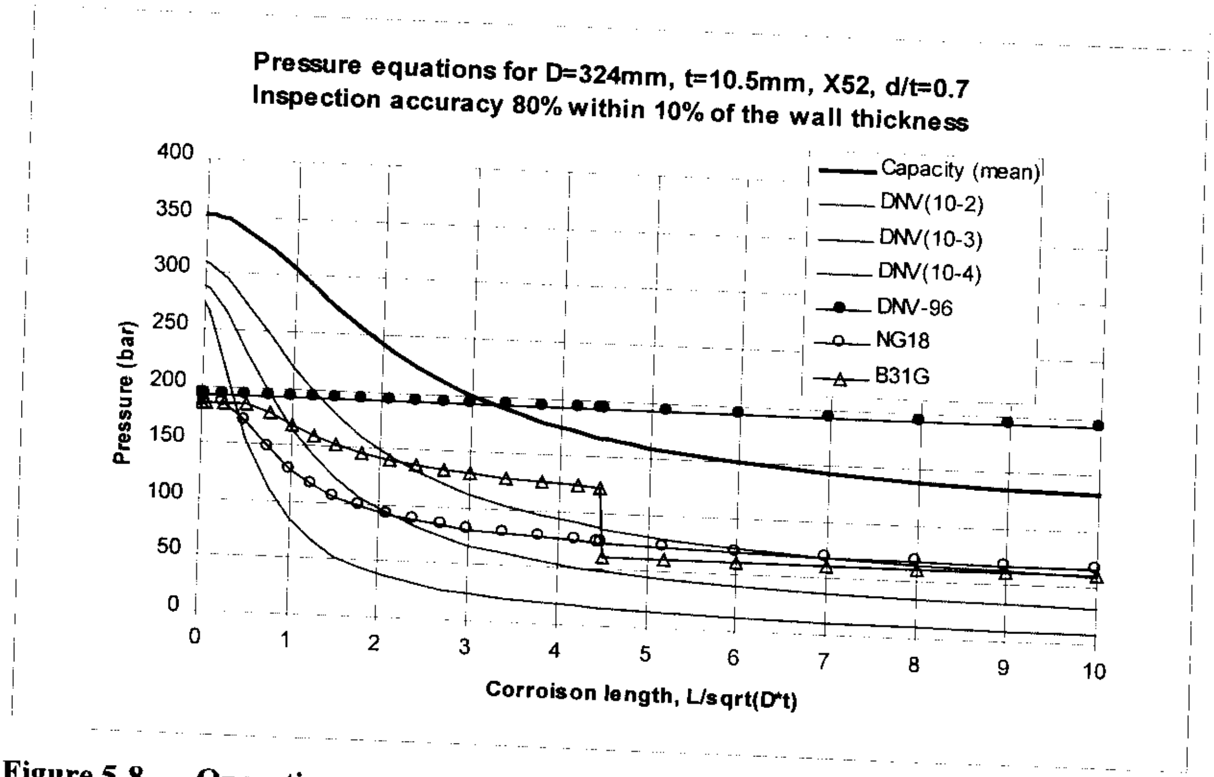


Figure 5-8 Operating pressure for 70% depth corrosion.

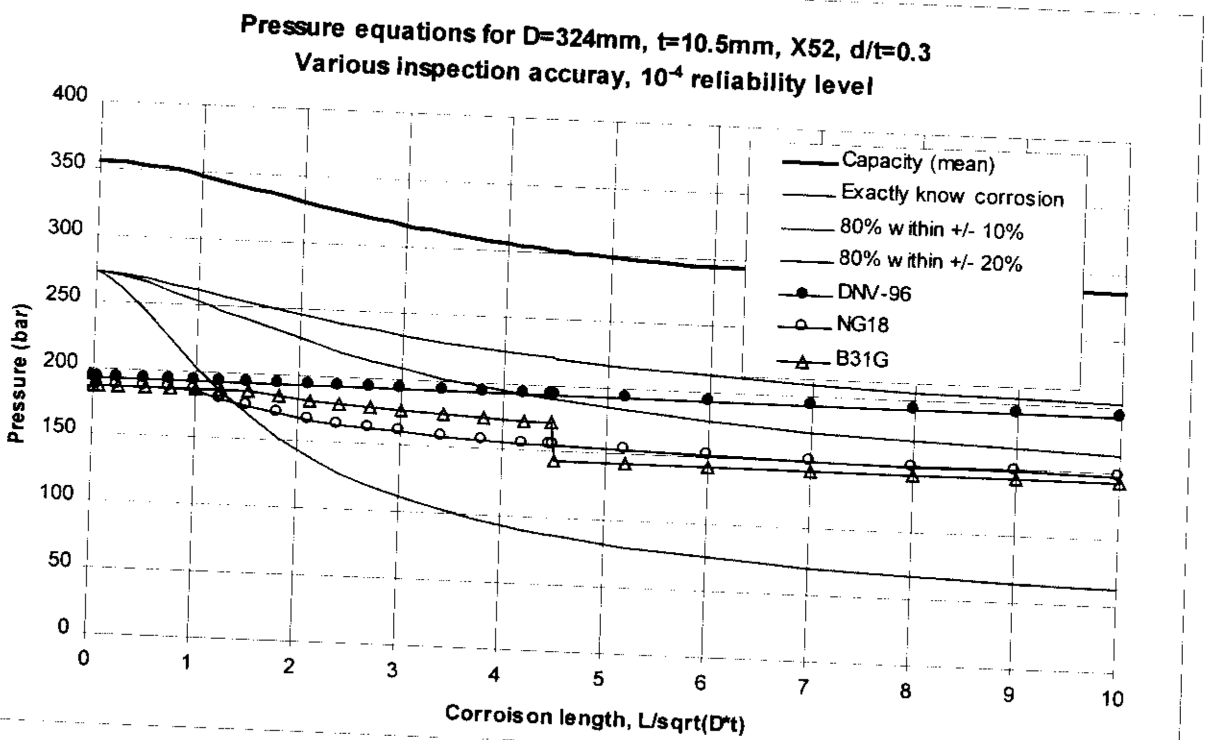


Figure 5-9 Operating pressure based on DNV acceptance equation (10^{-4}) for three levels of inspection accuracy having 30% measured depth corrosion.

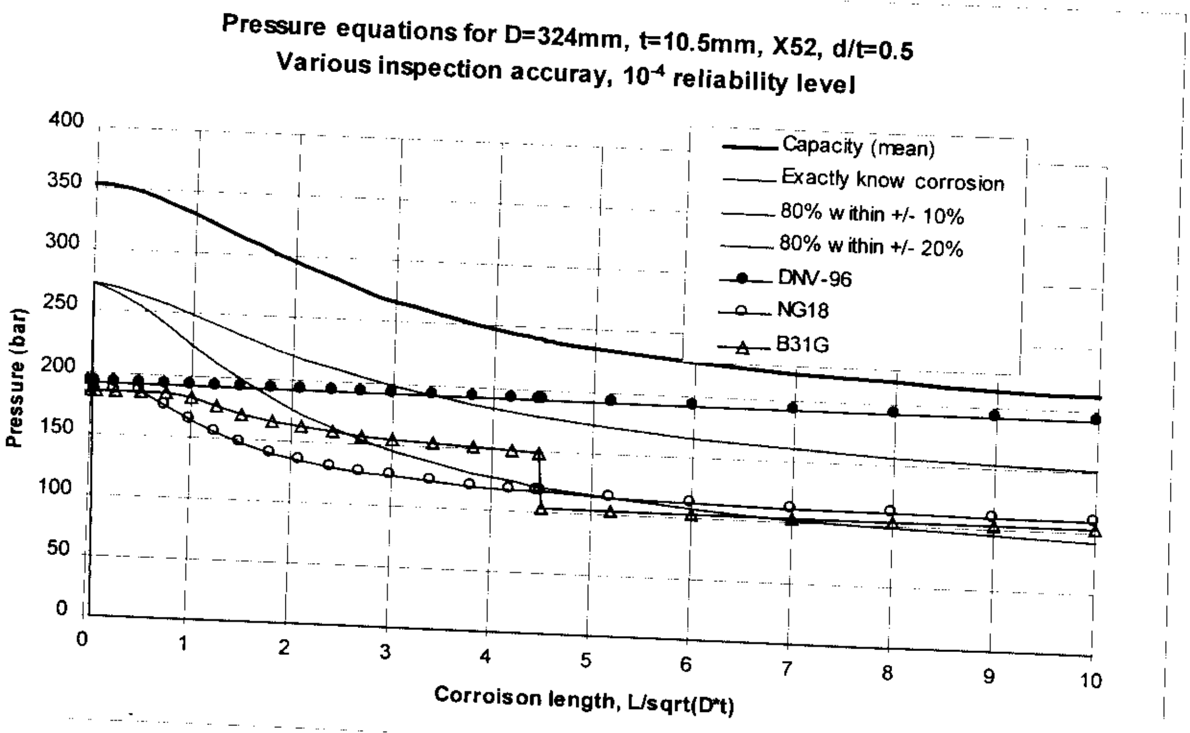


Figure 5-10 Operating pressure based on DNV acceptance equation (10^{-4}) for three levels of inspection accuracy having 50% measured depth corrosion.

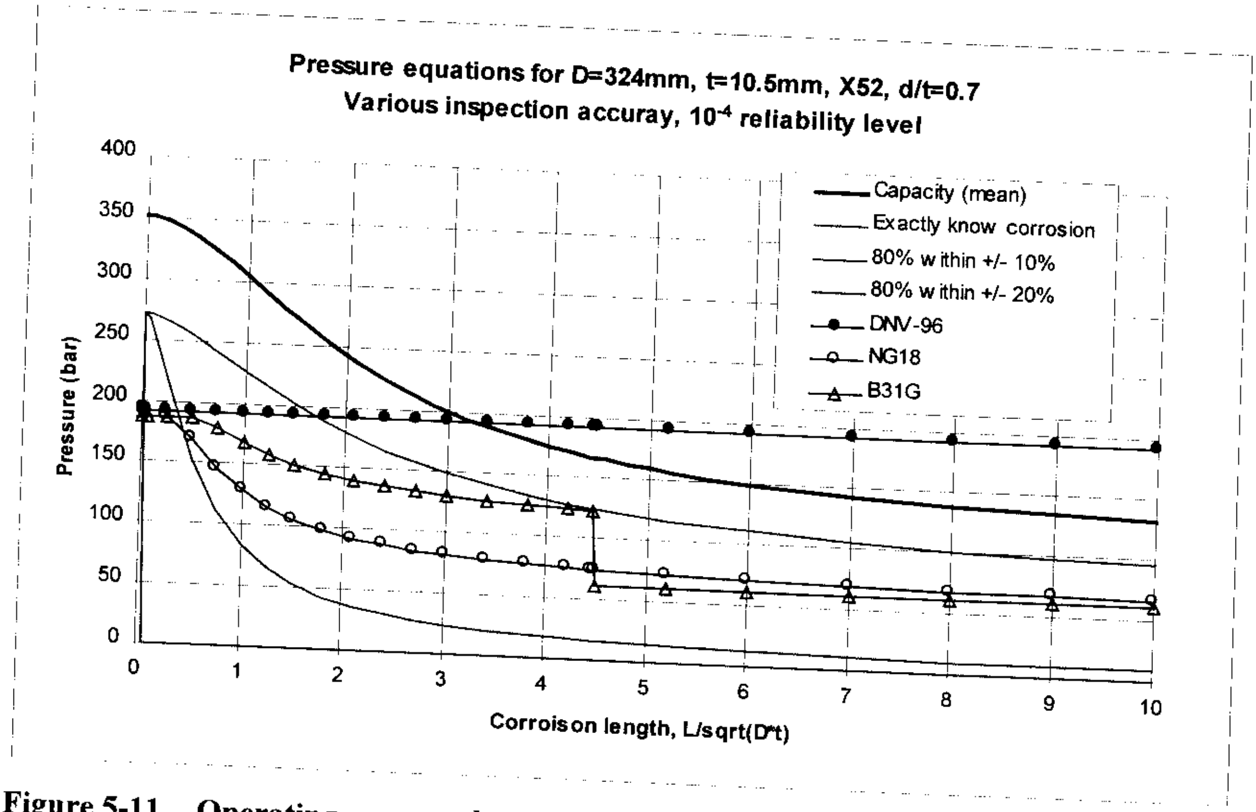


Figure 5-11 Operating pressure based on DNV acceptance equation (10^{-4}) for three levels of inspection accuracy having 70% measured depth corrosion.

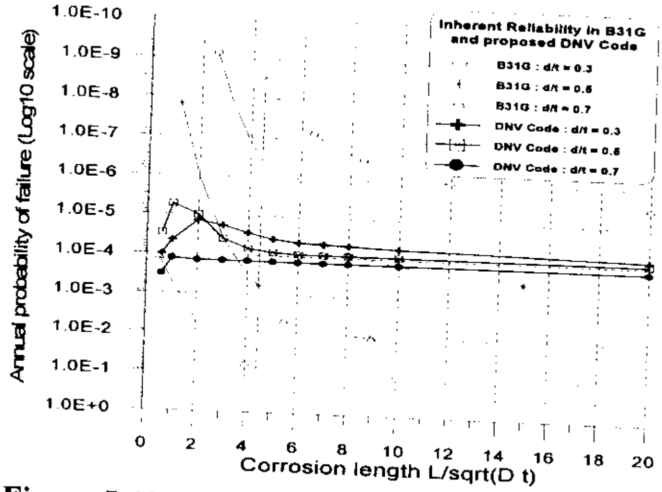


Figure 5-12 Inherent reliability level in B31G and in the proposed DNV acceptance equation for target reliability level 10^{-4}.

5.6 Partial Safety Factors

The following partial safety factors and fractile levels for the characteristic corrosion assessment values are defined depending on the target safety level and the degree of corrosion assessment accuracy in depth and length direction.

Safety level 10^{-2}

Assessment Accuracy:	Corrosion Length Standard Deviation. $Std[L]$:		
	Exact	15. mm	30. mm
Corrosion Depth: Exact:	$\gamma_M = 0.91$ $\gamma_d = 1.0$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	Not applicable	Not applicable
Corrosion Depth: 80% within 5 % of thickness $Std[d/t] = 4.\%$	$\gamma_M = 0.91$ $\gamma_d = 1.08$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.91$ $\gamma_d = 1.08$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.4$	$\gamma_M = 0.91$ $\gamma_d = 1.08$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.6$
Corrosion Depth: 80% within 10 % of thickness $Std[d/t] = 8.\%$	$\gamma_M = 0.91$ $\gamma_d = 1.14$ $\varepsilon_d = 0.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.91$ $\gamma_d = 1.14$ $\varepsilon_d = 0.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.91$ $\gamma_d = 1.14$ $\varepsilon_d = 0.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$
Corrosion Depth: 80% within 20 % of thickness $Std[d/t] = 16.\%$	$\gamma_M = 0.91$ $\gamma_d = 1.14$ $\varepsilon_d = 1.3$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.91$ $\gamma_d = 1.14$ $\varepsilon_d = 1.3$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.91$ $\gamma_d = 1.14$ $\varepsilon_d = 1.3$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$

Table 5-3 Partial safety factor and fractile values for 10^{-2} failure probability

Safety level 10^{-3}

Assessment Accuracy:	Corrosion Length Standard Deviation $Std[L]$:		
	Exact	15. mm	30. mm
Corrosion Depth: Exact:	$\gamma_M = 0.85$ $\gamma_d = 1.0$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	Not applicable	Not applicable
Corrosion Depth: 80% within 5 % of thickness $Std[d/t] = 4.\%$	$\gamma_M = 0.85$ $\gamma_d = 1.11$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.85$ $\gamma_d = 1.11$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.4$	$\gamma_M = 0.85$ $\gamma_d = 1.11$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.7$
Corrosion Depth: 80% within 10 % of thickness $Std[d/t] = 8.\%$	$\gamma_M = 0.85$ $\gamma_d = 1.24$ $\varepsilon_d = 0.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.85$ $\gamma_d = 1.24$ $\varepsilon_d = 0.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.85$ $\gamma_d = 1.24$ $\varepsilon_d = 0.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$
Corrosion Depth: 80% within 20 % of thickness $Std[d/t] = 16.\%$	$\gamma_M = 0.85$ $\gamma_d = 1.35$ $\varepsilon_d = 1.3$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.85$ $\gamma_d = 1.35$ $\varepsilon_d = 1.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.85$ $\gamma_d = 1.35$ $\varepsilon_d = 1.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$

Table 5-4 Partial safety factor and fractile values for 10^{-3} failure probability

Safety level 10^{-4}

Assessment Accuracy:	Corrosion Length Standard Deviation $Std[L]$:		
	Exact	15. mm	30. mm
Corrosion Depth: Exact:	$\gamma_M = 0.80$ $\gamma_d = 1.0$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	Not applicable	Not applicable
Corrosion Depth: 80% within 5 % of thickness $Std[d/t] = 4.\%$	$\gamma_M = 0.80$ $\gamma_d = 1.13$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.80$ $\gamma_d = 1.13$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.4$	$\gamma_M = 0.80$ $\gamma_d = 1.13$ $\varepsilon_d = 0.0$ $\gamma_L = 1.0$ $\varepsilon_L = 0.8$
Corrosion Depth: 80% within 10 % of thickness $Std[d/t] = 8.\%$	$\gamma_M = 0.80$ $\gamma_d = 1.32$ $\varepsilon_d = 0.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.80$ $\gamma_d = 1.32$ $\varepsilon_d = 0.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.80$ $\gamma_d = 1.32$ $\varepsilon_d = 0.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$
Corrosion Depth: 80% within 20 % of thickness $Std[d/t] = 16.\%$	$\gamma_M = 0.80$ $\gamma_d = 1.60$ $\varepsilon_d = 1.3$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.80$ $\gamma_d = 1.60$ $\varepsilon_d = 1.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$	$\gamma_M = 0.80$ $\gamma_d = 1.60$ $\varepsilon_d = 1.5$ $\gamma_L = 1.0$ $\varepsilon_L = 0.0$

Table 5-5 Partial safety factor and fractile values for 10^{-4} failure probability

5.7 Real Corrosion

The proposed acceptance equation for longitudinal corrosion has been defined for rectangular corrosion shapes only. The possible influence of other corrosion shapes on the burst capacity was not investigated in detail in this study.

However, in order to determine the burst acceptance pressure for arbitrary corrosion shapes, an approach based on the *Effective Area* method described (RSTRENG, Kiefner and Vieth 1989) could be applied.

For arbitrary corrosion shapes, the burst acceptance pressure is estimated assuming a rectangular corrosion shape, where the expression for the acceptance pressure defined in Equation (5.11) is applied. The corrosion length is, in order to cover different possible burst scenarios, defined for a series of different corrosion lengths, given as sub lengths of the total length of the corrosion attack. For each of the considered corrosion lengths, the corresponding corrosion depth to be applied is the average corrosion depth over the considered length of the corrosion attack.

The predicted burst acceptance pressure for the corrosion attack is determined as the lowest obtained burst pressure for the corrosion lengths considered.

The influence of possible interaction from multiple corrosion paths was not considered in this study. However, multiple corrosion paths may, as a first approximation, be considered applying the same philosophy as for the *Effective Area* method, where rectangular corrosion shapes with varying corrosion lengths and corresponding corrosion depths defined as the average depth over the considered corrosion length.

6 COMBINED LOADING FOR LONGITUDINAL CORROSION

6.1 General

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

Note, 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 longitudinal corrosion, attention should be given to the wide corrosion shapes, in order to also evaluate the corrosion shape against burst as for circumferential corrosion, see Section 7.

In the evaluation of burst of pipes with longitudinal corrosion for combined loading, only external axial compression and external bending moment with compression on the corrosion zone has been considered.

Corroded pipes (with local weakening) should be assessed as a load controlled condition even if the response is displacement controlled.

The burst capacities of the corroded pipes for these external load conditions have been derived based on a modelling of the allowable internal pressure and the longitudinal compressive stress level in the pipe,

$$\left(\frac{P_H}{P_{H0}}\right)^2 + \left(\frac{\sigma_L}{\sigma_{L0}}\right)^2 - \frac{P_H}{P_{H0}} \cdot \frac{\sigma_L}{|\sigma_{L0}|} = 1 \tag{6.12}$$

where P_H and σ_L are the allowable combined internal pressure level and longitudinal stress level at the location of the corrosion, and P_{H0} and σ_{L0} are the equivalent allowable limit values for solely internal pressure with no longitudinal stress and solely longitudinal stress with no internal pressure

The allowable internal pressure capacity is then defined as,

$$P_H = \frac{P_{H0}}{2} \cdot \left(\frac{\sigma_L}{|\sigma_{L0}|} + \sqrt{4 - 3\left(\frac{\sigma_L}{\sigma_{L0}}\right)^2} \right) \tag{6.13}$$

Note that σ_L is the longitudinal stress level in the pipe at pressure level P_H and that σ_L is negative for compression loads.

6.2 Global Yielding

A limitation in the allowable level of combined internal pressure and axial loading is the occurrence of global yielding from hoop stresses and axial stresses. The global von-Mieses yield criterion for the uncorroded (or generally corroded) area of the pipe will therefore establish a limitation for the allowable combination of internal pressure and axial loading, both for the capacity equation and the acceptance equation.

The von-Mieses yield criterion is to be based on the mean value for the yield stress.

$$E[\sigma_y] = \sqrt{\sigma_H^2 + \sigma_L^2 - \sigma_H \sigma_L}$$

If no other information is available, the mean value for the yield stress may be defined as $(\text{SMYS} = \mu - 2\sigma$, and $\text{CoV} = 4\%)$

$$E[\sigma_y] = \frac{1}{0.92} \cdot \text{SMYS}$$

For combinations of internal pressure and axial loading being limited by the global von-Mieses yield criterion, an increase in the internal pressure level until the global von-Mieses yield curve interacts with the burst capacity curve (or burst acceptance curve for specified target reliability level) is permitted.

6.3 Capacity Equation

The capacity equation for the burst pressure capacity for combined internal pressure and axial compression is defined as,

$$P_C = \frac{P_{C0}}{2} \cdot \left(\frac{\sigma_L}{|\sigma_{L0}|} + \sqrt{4 - 3\left(\frac{\sigma_L}{\sigma_{L0}}\right)^2} \right) \tag{6.14}$$

where σ_L is the longitudinal stress level in the pipe at pressure level P_C.

In the modelling of the burst capacity for combined loading, the limit values for pure internal pressure is defined from the capacity equation for corroded pipes in Section 4.4.

$$P_{C0} = \frac{1}{\xi} \cdot P_{fit}$$

where ξ is the reduction factor in the burst pressure capacity for zero-axial stress (due to end-cap effects),

$$\xi = 1.15$$

The limit value for pure axial loading is defined from the tensile strength σ_u.

$$\sigma_{L0} = \sigma_u$$

The stress level considered is the longitudinal stress in the pipe wall at the site of the corrosion. In the computation of the longitudinal stress in the pipe σ_L due to external axial or bending loads, the influence of the local corrosion must be accounted for. End cap effects and thermal stresses must, further, be included in the determination of the longitudinal stress level.

In Figure 6-13 the burst pressure capacity depending on the level of external loading is sketched. Note the limitation in the allowable combination of internal pressure and axial stress level due to global yielding.

Figure 6-13 Burst pressure capacities depending on the level of external loading

6.4 Acceptance Equation

In the evaluation of the acceptance equation for the mean annual maximum operating pressure $E[P_A]$ for combined internal pressure and external loading, the same approach as for the burst capacity formulation is applied.

However, the proposed acceptance equation for combined loading has in this study not been based on a probabilistic calibration.

The acceptance equation for the burst pressure for combined internal pressure and axial compression is defined as,

$$E[P_A] = \frac{E[P_{A0}]}{2} \cdot \left(\frac{\sigma_L}{|\sigma_{L0}|} + \sqrt{4 - 3\left(\frac{\sigma_L}{\sigma_{L0}}\right)^2} \right) \qquad \textbf{(6.15)}$$

where σ_L is the longitudinal stress level in the pipe at pressure level $E[P_A]$.

The limit value for zero longitudinal stress is defined from the mean value for the annual maximum operating pressure $E[P_{INT}]$ according to the acceptance equation for corroded pipes in Section 5.4,

$$E[P_{A0}] = \frac{1}{\xi} \cdot E[P_{INT}]$$

The value of $E[P_{INT}]$ is defined depending on the desired safety level and the accuracy of the corrosion assessment.

The limit value for zero hoop stress is defined from the specified minimum tensile strength SMTS,

- $\sigma_{L0} = \text{SMTS}$

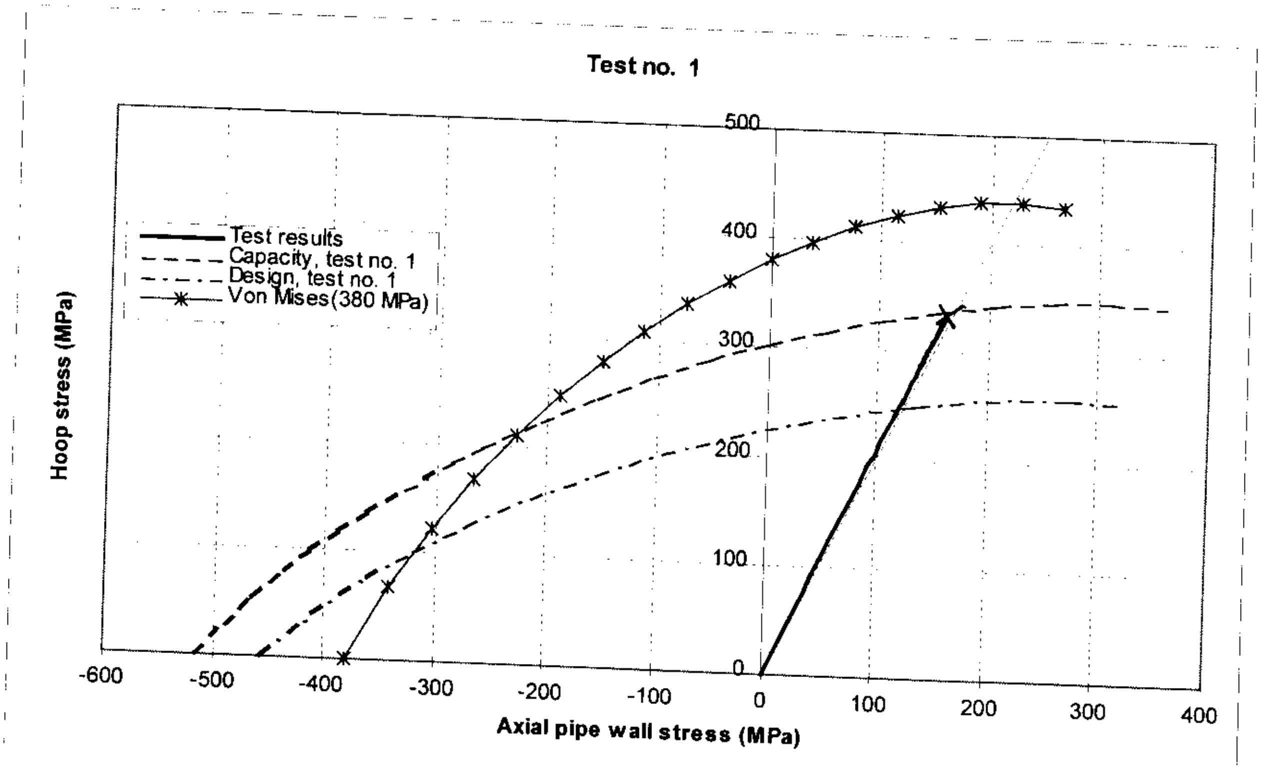
The stress level considered is the longitudinal stress in the pipe wall at the site of the corrosion. In the computation of the longitudinal stress in the pipe σ_L due to external axial or bending loads, the influence of the local corrosion must be accounted for. End cap effects and thermal stresses must, further, be included in the determination of the longitudinal stress level.

In Figure 6-14 the acceptance equation for the mean annual maximum operating pressure depending on the level of external loading is sketched for three different probability levels for longitudinal corrosion. Note the limitation in the allowable combination of internal pressure and axial stress level due to global yielding.

include fig.

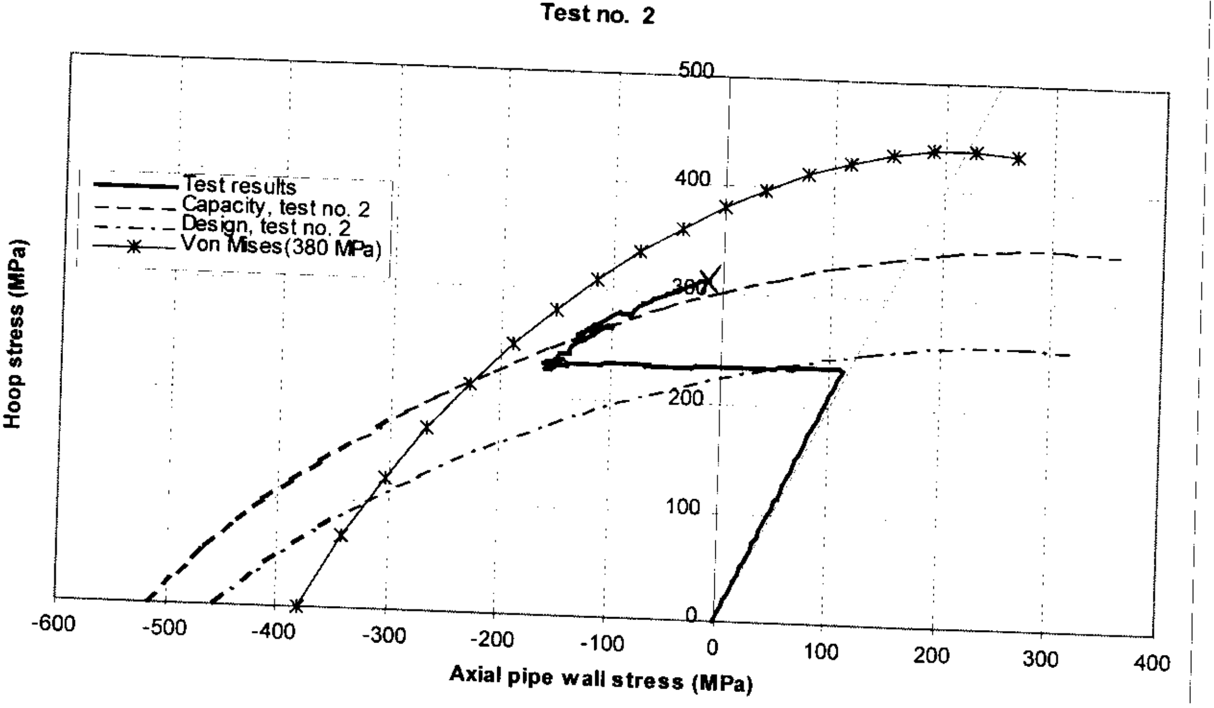
Figure 6-14 Mean values for the allowable operating pressure depending on the level of external loading for the probability levels 10^{-2}, 10^{-3} and 10^{-4}.

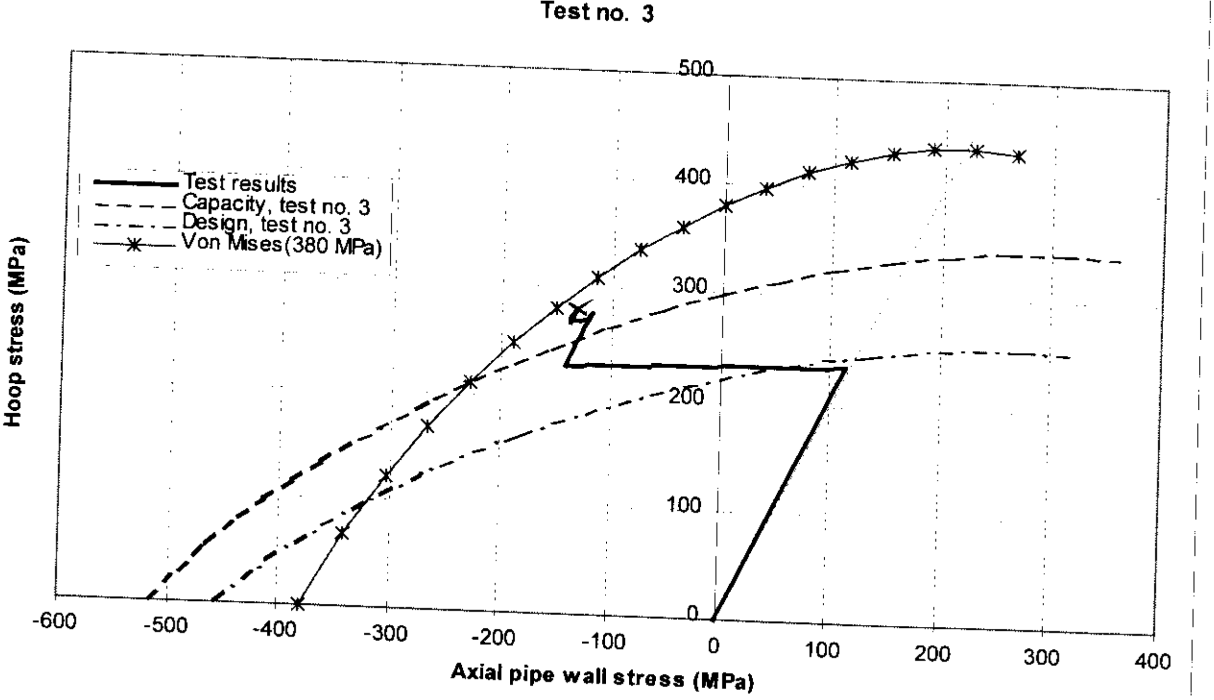
6.5 Comparison with tests



Modified σax for corroded area will be evaluated.

Fig text.


Test no. 2
Test results
Capacity, test no. 2
Design, test no. 2
Von Mises(380 MPa)
Hoop stress (MPa)
Axial pipe wall stress (MPa)
0
100
200
300
400
500
-600
-500
-400
-300
-200
-100
0
100
200
300
400


Test no. 3
Test results
Capacity, test no. 3
Design, test no. 3
Von Mises(380 MPa)
Hoop stress (MPa)
Axial pipe wall stress (MPa)
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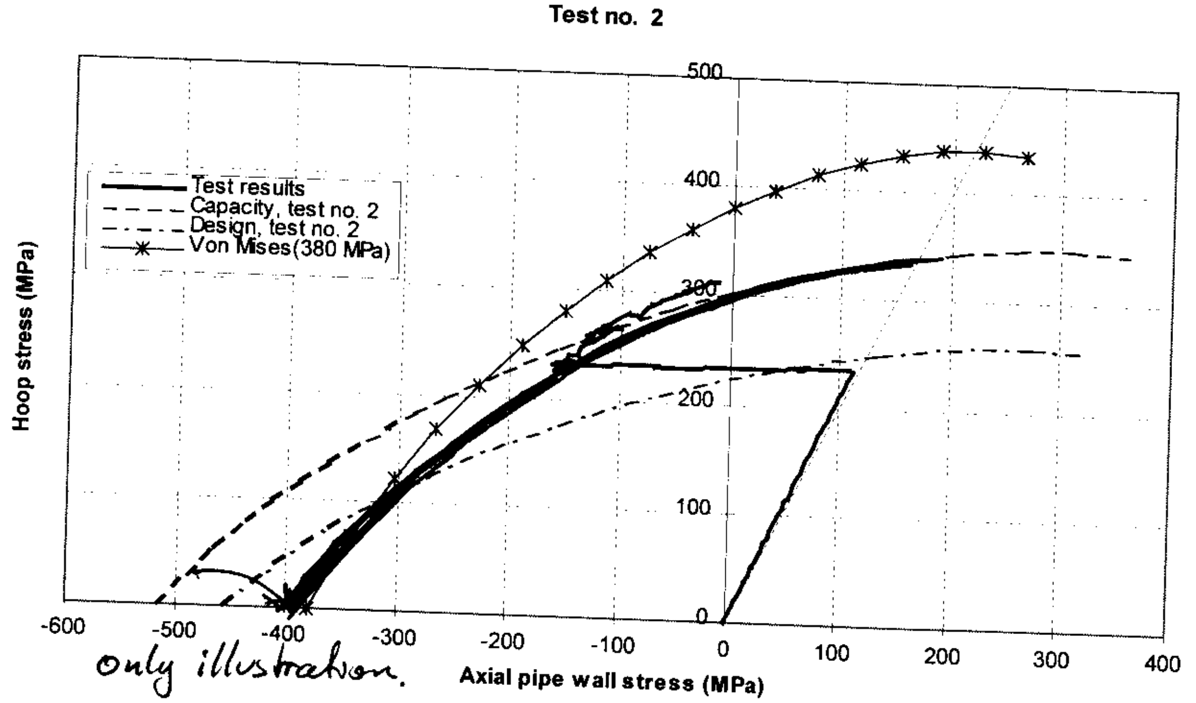
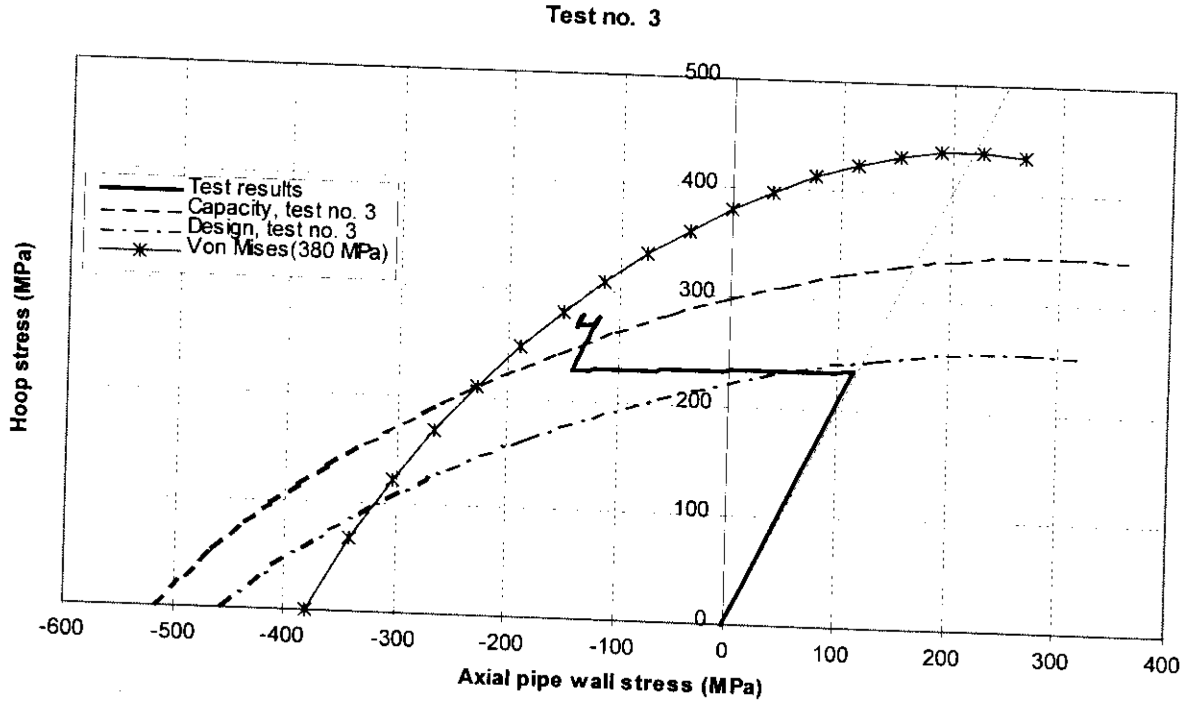
100
200
300
400
500
-600
-500
-400
-300
-200
-100
0
100
200
300
400



only illustration.

→ redused area, modified σax for test 1, 2 and 3



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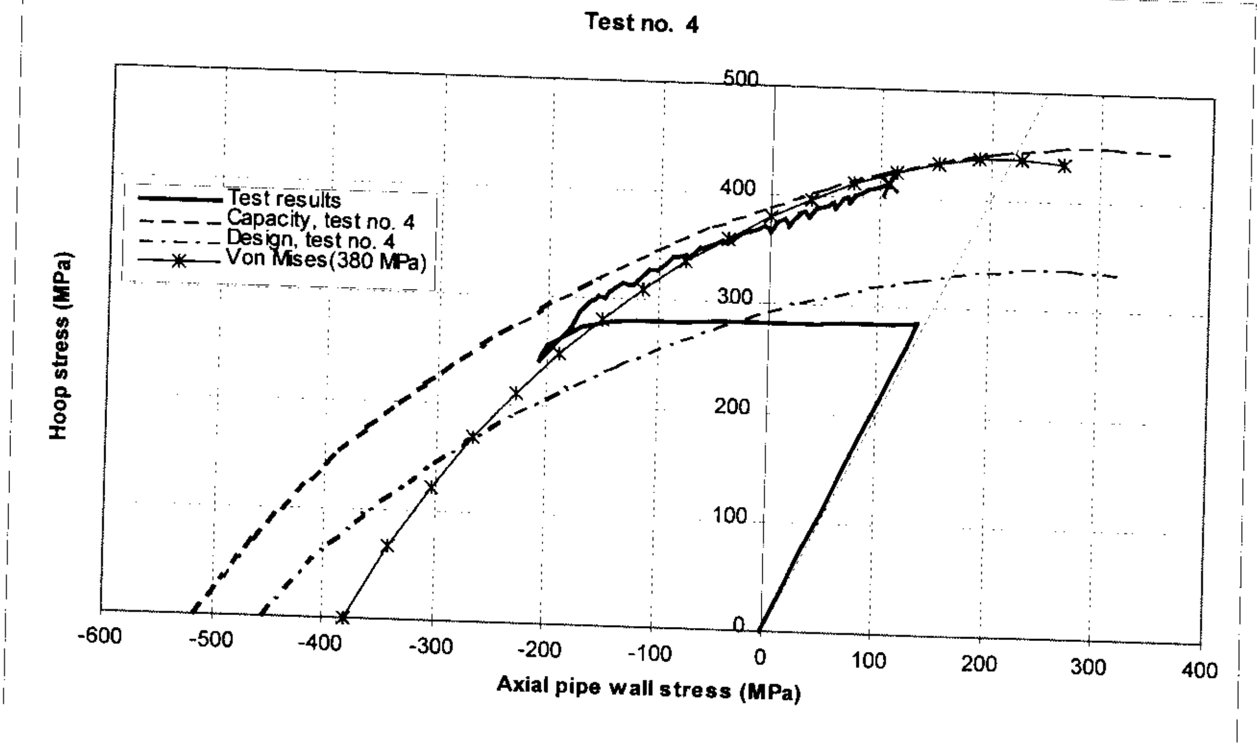
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Test results
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Design, test no. 4
Von Mises(380 MPa)
Hoop stress (MPa)
Axial pipe wall stress (MPa)
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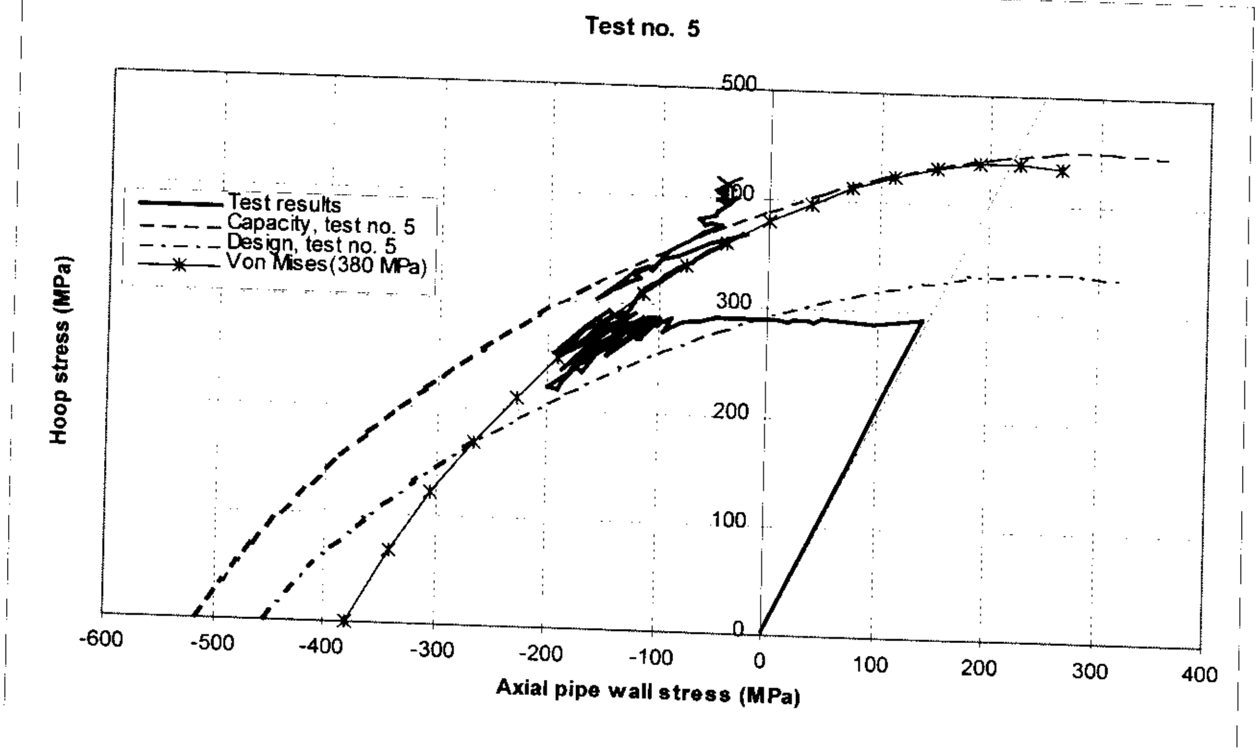
400
300
200
100
0
-600
-500
-400
-300
-200
-100
0
100
200
300
400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Test results
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Design, test no. 5
Von Mises(380 MPa)
Hoop stress (MPa)
Axial pipe wall stress (MPa)
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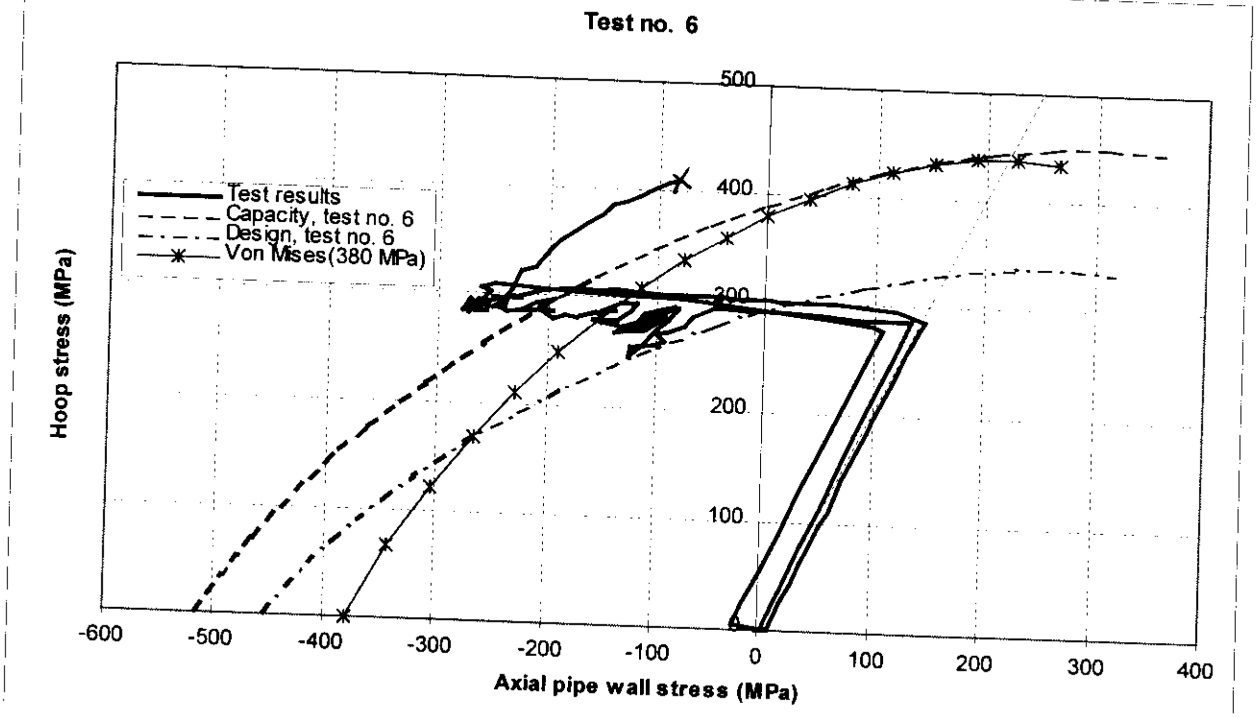
300
200
100
0
-600
-500
-400
-300
-200
-100
0
100
200
300
400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Test results
Capacity, test no. 6
Design, test no. 6
Von Mises(380 MPa)
Hoop stress (MPa)
Axial pipe wall stress (MPa)
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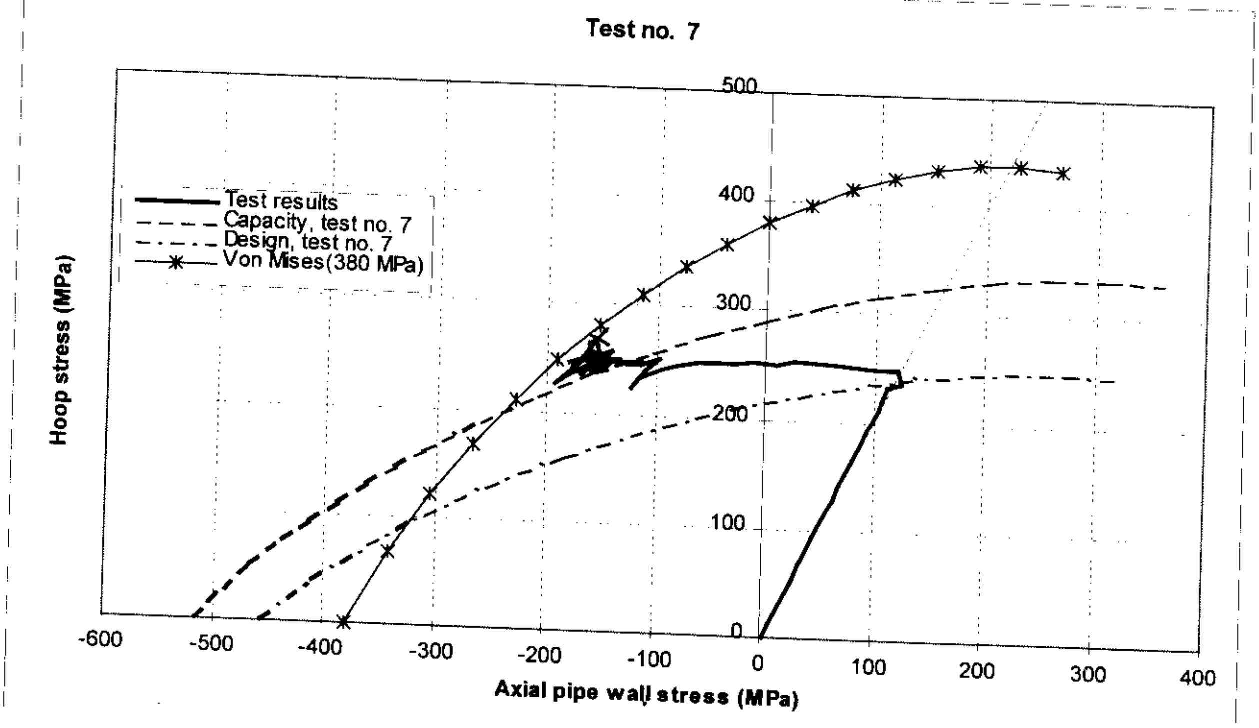
300
200
100
-600
-500
-400
-300
-200
-100
0
100
200
300
400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Test results
Capacity, test no. 7
Design, test no. 7
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Hoop stress (MPa)
Axial pipe wall stress (MPa)
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200
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-500
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-200
-100
0
100
200
300
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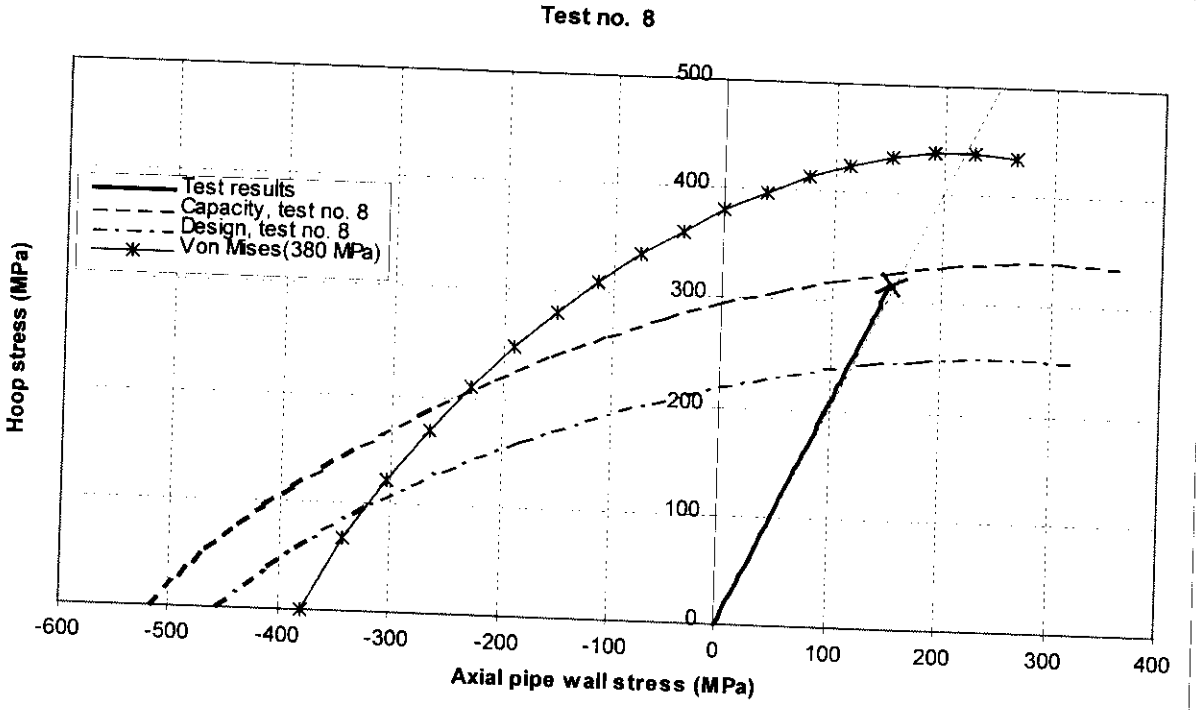
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Design, test no. 8
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Hoop stress (MPa)
Axial pipe wall stress (MPa)
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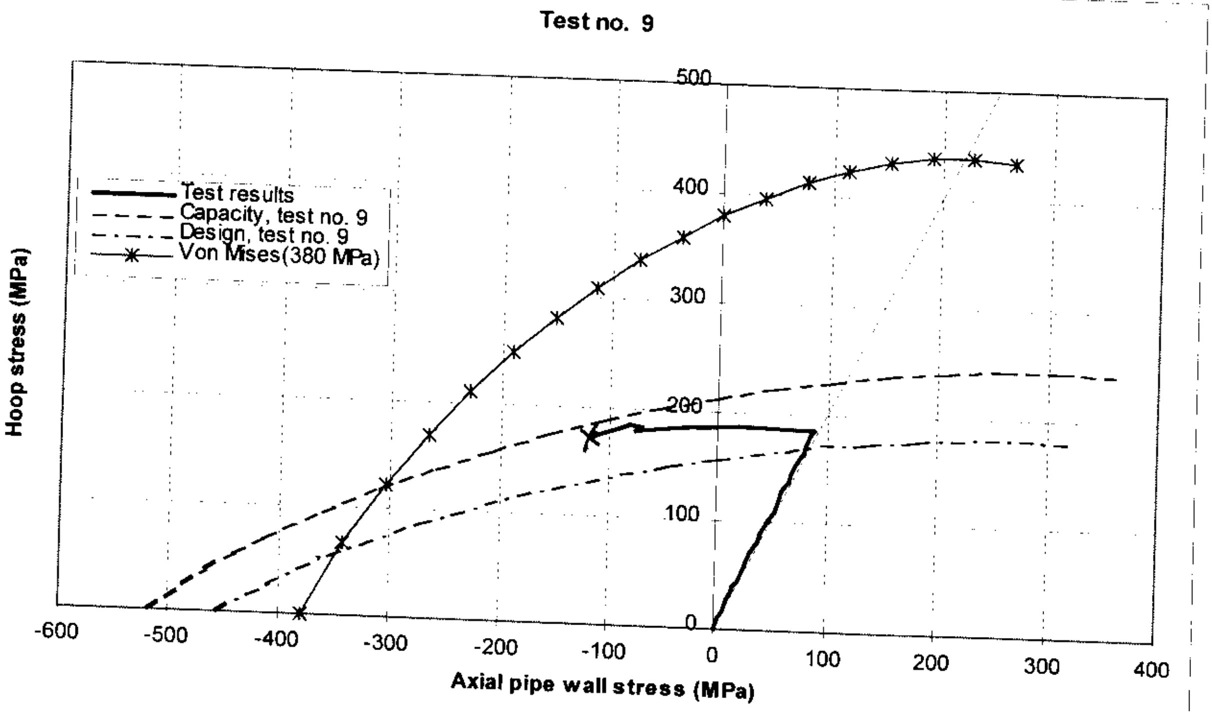
-200
-100
0
100
200
300
400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Test results
Capacity, test no. 9
Design, test no. 9
Von Mises(380 MPa)
Hoop stress (MPa)
Axial pipe wall stress (MPa)
500
400
300
200
100
0
-600
-500
-400
-300
-200
-100
0
100
200
300
400

7 COMBINED LOADING FOR CIRCUMFERENTIAL CORROSION

7.1 General

Proposed capacity and acceptance equations for burst of circumferential corroded pipes having combined internal pressure and external loading are defined in the following.

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

In the evaluation of circumferential corrosion, attention should be given to the longitudinal length of the corrosion, in order to also evaluate the corrosion shape against burst as for longitudinal corrosion, see Section 6.

In the evaluation of burst of pipes with circumferential corrosion for combined loading, only external axial compression and external bending moment with compression on the corrosion zone has been considered.

Corroded pipes (with local weakening) should be assessed as a load controlled condition even if the response is displacement controlled.

The burst capacities of the corroded pipes for these external load conditions have been derived based on a modelling of the allowable internal pressure and the longitudinal compressive stress level in the pipe,

$$\left(\frac{P_H}{P_{H0}}\right)^2 + \left(\frac{\sigma_L}{\sigma_{L0}}\right)^2 - \frac{P_H}{P_{H0}} \cdot \frac{\sigma_L}{|\sigma_{L0}|} = 1 \qquad (7.16)$$

where P_H and σ_L are the allowable combined internal pressure level and longitudinal stress level at the location of the corrosion, and P_{H0} and σ_{L0} are the equivalent allowable limit values for solely internal pressure with no longitudinal stress and solely longitudinal stress with no internal pressure

The allowable internal pressure capacity is then defined as,

$$P_H = \frac{P_{H0}}{2} \cdot \left(\frac{\sigma_L}{|\sigma_{L0}|} + \sqrt{4 - 3\left(\frac{\sigma_L}{\sigma_{L0}}\right)^2} \right) \qquad (7.17)$$

Note that σ_L is the longitudinal stress level in the pipe at pressure level P_H and that σ_L is negative for compression loads.

7.2 Global Yielding

A limitation in the allowable level of combined internal pressure and axial loading is the occurrence of global yielding from hoop stresses and axial stresses. The global von-Mieses yield criterion for the uncorroded (or generally corroded) area of the pipe will therefore establish a limitation for the allowable combination of internal pressure and axial loading, both for the capacity equation and the acceptance equation.

The von-Mieses yield criterion is to be based on the mean value for the yield stress.

$$E[\sigma_y] = \sqrt{\sigma_H^2 + \sigma_L^2 - \sigma_H \sigma_L}$$

If no other information is available, the mean value for the yield stress may be defined as

$$E[\sigma_y] = \frac{1}{0.92} \cdot \text{SMYS}$$

For combinations of internal pressure and axial loading being limited by the global von-Mieses yield criterion, an increase in the internal pressure level until the global von-Mieses yield curve interacts with the burst capacity curve (or burst acceptance curve for specified target reliability level) is permitted.

7.3 Capacity Equation

The capacity equation for the burst pressure capacity for combined internal pressure and axial compression is defined as,

$$P_C = \frac{P_{C0}}{2} \cdot \left(\frac{\sigma_L}{|\sigma_{L0}|} + \sqrt{4 - 3\left(\frac{\sigma_L}{\sigma_{L0}}\right)^2} \right) \tag{7.18}$$

where σ_L is the longitudinal stress level in the pipe at pressure level P_{Cap}.

The limit burst pressure for zero longitudinal stress is,

$$P_{C0} = \frac{1}{\xi} \cdot \frac{2 \cdot t}{D - t} \cdot \sigma_u \cdot \left(1.25 - 0.70 \cdot \frac{\sigma_y}{\sigma_u} + 0.70 \cdot \left(\frac{\sigma_y}{\sigma_u}\right)^2 \right) \tag{7.19}$$

where

$$\xi = 1.15$$

For a yield strength - tensile strength ratio of 0.83, the limit hoop stress is equal to the ultimate tensile strength.

The limit longitudinal stress for zero hoop stress is defined from the tensile strength σ_u,

$$\sigma_{L0} = \sigma_u$$

In the computation of the longitudinal stress level in the pipe σ_L for the burst pressure capacity evaluation, the influence of the local corrosion may be omitted.

The influence of end cap effects and thermal stresses must, however, be accounted for in the determination of the longitudinal stress.

The local longitudinal stress level in the pipe at the site of the circumferential corrosion, accounting for the metal loss due to corrosion, is not to exceed the tensile stress,

$$|\sigma_{L-local}| \le \sigma_u$$

In Figure 7-15 the burst pressure capacity depending on the level of external loading is sketched for circumferential corrosion. Note the limitation in the allowable combination of internal pressure and axial stress level due to global yielding, and the constraint on the local longitudinal stress level at the site of corrosion (σ_u).

Figure 7-15 Burst pressure capacity for circumferential corrosion

7.4 Acceptance Equation

In the evaluation of the acceptance equation for the mean annual maximum operating pressure $E[P_A]$ for combined internal pressure and external loading having circumferential corrosion, the same approach as for the burst capacity formulation is applied.

However, the proposed acceptance equation for circumferential corrosion has in this study not been based on a probabilistic calibration for combined loading.

The acceptance equation for the burst pressure for combined internal pressure and axial compression for circumferential corrosion is defined as,

$$E[P_A] = \frac{E[P_{A0}]}{2} \cdot \left(\frac{\sigma_L}{|\sigma_{L0}|} + \sqrt{4 - 3\left(\frac{\sigma_L}{\sigma_{L0}} \right)^2} \right) \qquad (7.20)$$

where σ_L is the longitudinal stress level in the pipe at pressure level $E[P_A]$.

The limit value for zero longitudinal stress is,

$$E[P_{A0}] = \frac{1}{\xi} \cdot \frac{2 \cdot t}{D - t} \cdot \gamma_M \cdot \mathrm{SMTS} \cdot \left(0.80 + 0.40 \cdot \frac{\mathrm{SMYS}}{\mathrm{SMTS}} \right) \qquad (7.21)$$

where $\xi = 1.15$ and γ_M is the model prediction partial safety factor from Table 5-3, Table 5-4 and Table 5-5.

The limit longitudinal stress for zero hoop stress is defined from the specified minimum tensile strength SMTS,

$$\sigma_{L0} = \mathrm{SMTS}$$

In the computation of the longitudinal stress level in the pipe σ_L due the external axial and bending loads, the influence of the local corrosion may be omitted. End cap effects and thermal stresses must, however, be accounted for in the determination of the longitudinal stress.

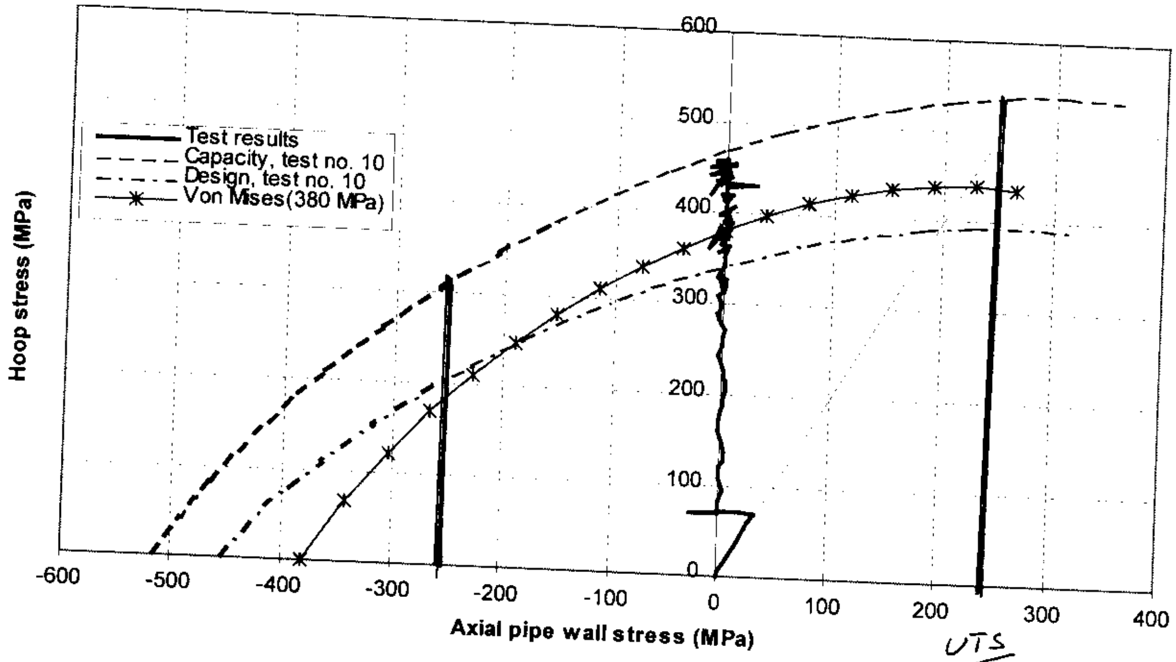
However, the local longitudinal stress level in the pipe at the site of the circumferential corrosion, accounting for the metal loss due to corrosion, is not to exceed the specified minimum tensile strength,

$$\left|\sigma_{L\text{-}local}\right| \leq \mathrm{SMTS}$$

In Figure 7-16 the acceptance equation for the mean annual maximum operating pressure depending on the level of external loading is sketched for three different probability levels for circumferential corrosion. Note the limitation in the allowable combination of internal pressure and axial stress level due to global yielding and the constraint on the local longitudinal stress level at the site of corrosion (SMTS).

Figure 7-16 **Mean value for the allowable pressure for circumferential corrosion for the probability levels 10^{-2}, 10^{-3} and 10^{-4}.**

Test no. 10



UTS/2

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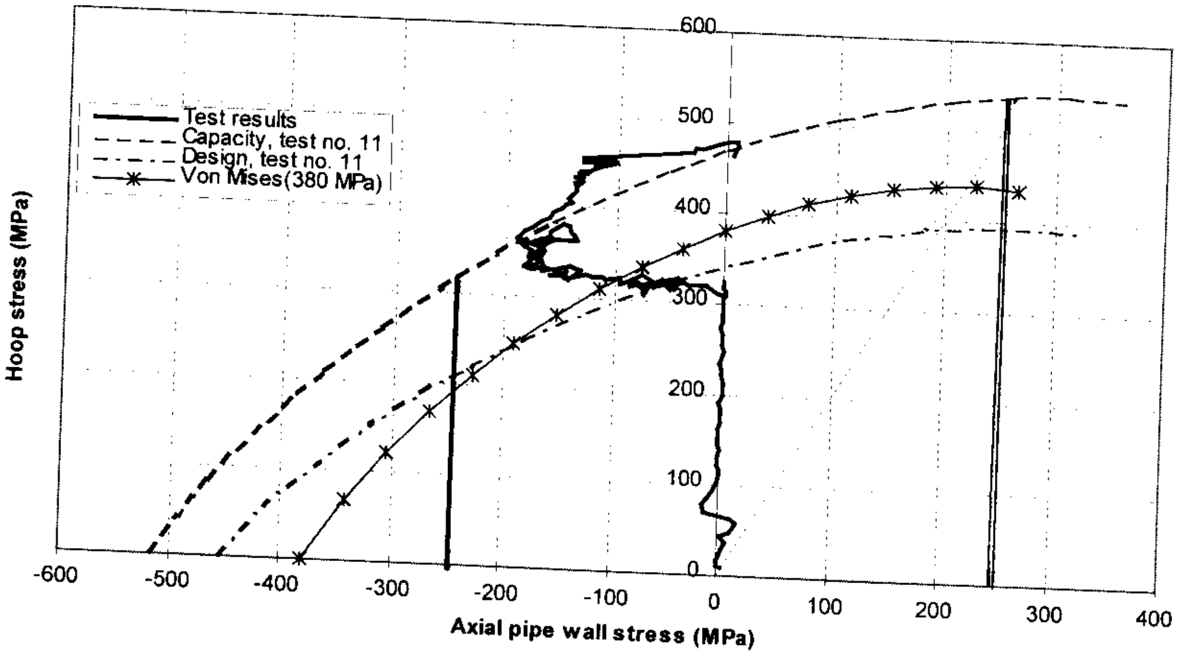

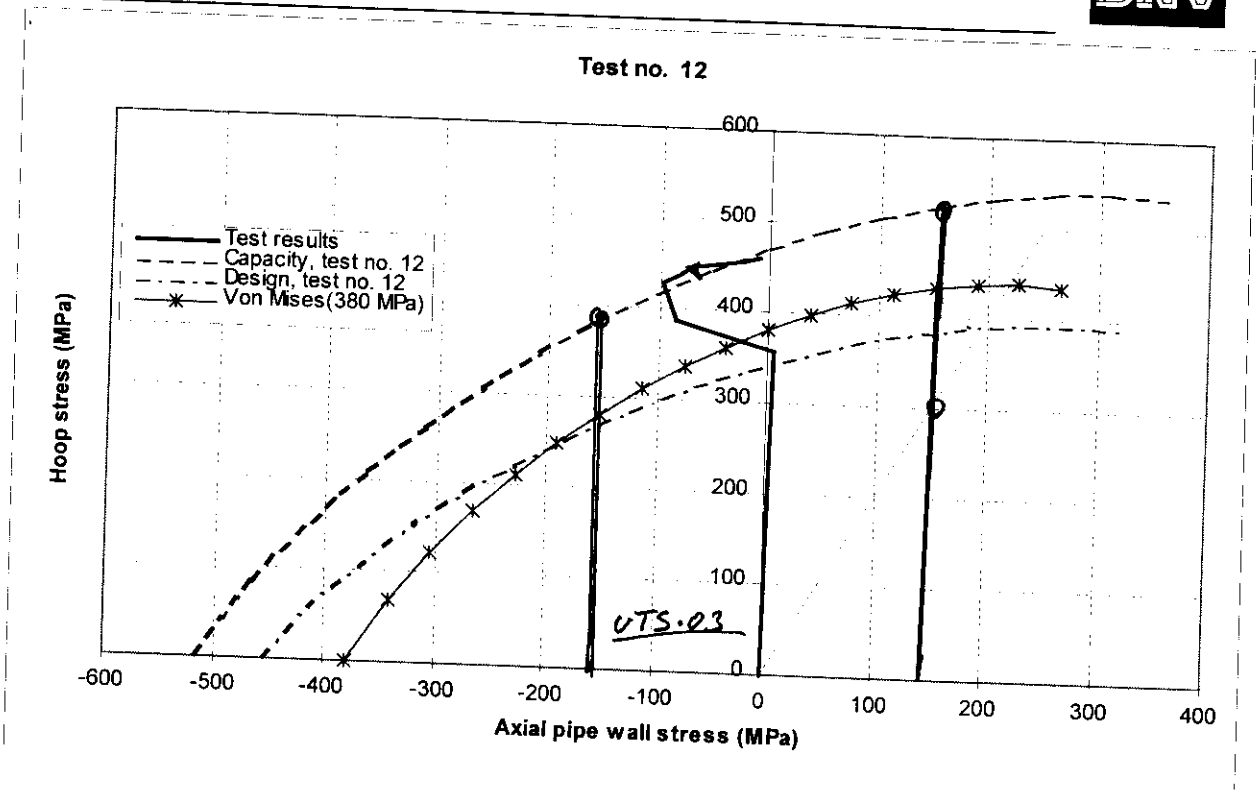

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