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DNV

# TECHNICAL REPORT

# JOINT INDUSTRY PROJECT

## RELIABILITY OF CORRODED PIPES
## PROJECT GUIDELINE

REPORT NO. 97-3358

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DET NORSKE VERITAS

# 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 presented in this project guideline.

# 2 INTRODUCTION

## 2.1 Background

The DNV JIP project "*Reliability of Corroded Pipes*" has been conducted with the following participants:

| Participants | Respresentative |
|---|---|
| Minerals Management Service (MMS) | Wallace O. Adcox |
| Norwegian Petroleum Directorate (NPD) | Kjell A. Anfinsen |
| Den norske stats oljeselskap a.s.(Statoil) | Richard Verley |
| Amoco Norway Oil Company (Amoco) | Ole Jørgen Narvestad |
| Exxon Production Research Company (EPR) | Robert Appleby |
| Petrobras /CENPES/DIPREX | Adilson C. Benjamin |

## 2.2 Assumptions

## 2.3 Real Corrosion

The proposed acceptance equation for longitudinal corrosion has been defined for rectangular corrosion shapes only.

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

For arbitrary corrosion shapes, the burst acceptance pressure is estimated assuming a rectangular corrosion shape. However, 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.

## 2.4 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.

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,

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

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 acceptance curve for specified target reliability level is permitted.

# 3 LONGITUDINAL CORROSION

## 3.1 Internal Pressure

The acceptance equation for the mean value of the annual maximum operating pressure is,

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

where

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

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

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

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

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,

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

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

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

- $\gamma_M$ : Model prediction
- $\gamma_d$ : Corrosion depth assessment
- $\varepsilon_d$: Fractile level for corrosion depth
- $\gamma_L$ : Corrosion length assessment
- $\varepsilon_L$: 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 Section 3.3.
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

## 3.2 Combined Loading

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

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

where $\sigma_L$ 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 3.1,

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

$E[P_{INT}]$ 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,

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

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 $\sigma_L$ 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.

## 3.3 Partial Safety Factors

| **Assessment Accuracy** | **Corrosion Length: Standard Deviation** | | |
|---|---|---|---|
| | **0. mm** | **15. mm** | **30. mm** |
| **Corrosion Depth: Exact** | $\gamma_m = 0.91$<br>$\gamma_d = 1.0$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | Not Applicable | Not Applicable |
| **Corrosion Depth: 80% within ± 5% *t*** | $\gamma_m = 0.91$<br>$\gamma_d = 1.08$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.91$<br>$\gamma_d = 1.08$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.4$ | $\gamma_m = 0.91$<br>$\gamma_d = 1.08$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.6$ |
| **Corrosion Depth: 80% within ± 10% *t*** | $\gamma_m = 0.91$<br>$\gamma_d = 1.14$ $\varepsilon_d = 0.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.91$<br>$\gamma_d = 1.14$ $\varepsilon_d = 0.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.91$<br>$\gamma_d = 1.14$ $\varepsilon_d = 0.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ |
| **Corrosion Depth: 80% within ± 20% *t*** | $\gamma_m = 0.91$<br>$\gamma_d = 1.14$ $\varepsilon_d = 1.3$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.91$<br>$\gamma_d = 1.14$ $\varepsilon_d = 1.3$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.91$<br>$\gamma_d = 1.14$ $\varepsilon_d = 1.3$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ |

**Table 1** **Partial safety factors and fractile values for $10^{-2}$ failure probability**

| Assessment Accuracy | Corrosion Length: Standard Deviation | | |
|---|---|---|---|
| | 0. mm | 15. mm | 30. mm |
| **Corrosion Depth: Exact** | $\gamma_m = 0.85$<br>$\gamma_d = 1.0$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | Not Applicable | Not Applicable |
| **Corrosion Depth: 80% within ± 5% *t*** | $\gamma_m = 0.85$<br>$\gamma_d = 1.11$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.85$<br>$\gamma_d = 1.11$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.4$ | $\gamma_m = 0.85$<br>$\gamma_d = 1.11$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.7$ |
| **Corrosion Depth: 80% within ± 10% *t*** | $\gamma_m = 0.85$<br>$\gamma_d = 1.24$ $\varepsilon_d = 0.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.85$<br>$\gamma_d = 1.24$ $\varepsilon_d = 0.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.85$<br>$\gamma_d = 1.24$ $\varepsilon_d = 0.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ |
| **Corrosion Depth: 80% within ± 20% *t*** | $\gamma_m = 0.85$<br>$\gamma_d = 1.35$ $\varepsilon_d = 1.3$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.85$<br>$\gamma_d = 1.35$ $\varepsilon_d = 1.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.85$<br>$\gamma_d = 1.35$ $\varepsilon_d = 1.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ |

**Table 2 Partial safety factors and fractile values for $10^{-3}$ failure probability**

| Assessment Accuracy | Corrosion Length: Standard Deviation | | |
|---|---|---|---|
| | 0. mm | 15. mm | 30. mm |
| **Corrosion Depth: Exact** | $\gamma_m = 0.80$<br>$\gamma_d = 1.0$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | Not Applicable | Not Applicable |
| **Corrosion Depth: 80% within ± 5% *t*** | $\gamma_m = 0.80$<br>$\gamma_d = 1.13$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.80$<br>$\gamma_d = 1.13$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.4$ | $\gamma_m = 0.80$<br>$\gamma_d = 1.13$ $\varepsilon_d = 0.0$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.8$ |
| **Corrosion Depth: 80% within ± 10% *t*** | $\gamma_m = 0.80$<br>$\gamma_d = 1.32$ $\varepsilon_d = 0.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.80$<br>$\gamma_d = 1.32$ $\varepsilon_d = 0.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.80$<br>$\gamma_d = 1.32$ $\varepsilon_d = 0.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ |
| **Corrosion Depth: 80% within ± 20% *t*** | $\gamma_m = 0.80$<br>$\gamma_d = 1.60$ $\varepsilon_d = 1.3$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.80$<br>$\gamma_d = 1.60$ $\varepsilon_d = 1.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ | $\gamma_m = 0.80$<br>$\gamma_d = 1.60$ $\varepsilon_d = 1.5$<br>$\gamma_L = 1.0$ $\varepsilon_L = 0.0$ |

**Table 3 Partial safety factors and fractile values for $10^{-4}$ failure probability**

# 4 CIRCUMFERENTIAL CORROSION

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

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

where $\sigma_L$ is the longitudinal stress level in the pipe at pressure level $E[P_A]$.
The limit value for zero longitudinal stress is,

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

where $\xi = 1.15$ and $\gamma_M$ is the model prediction partial safety factor from Section 3.3.
The limit longitudinal stress for zero hoop stress is defined from the specified minimum tensile strength,

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

In the computation of the longitudinal stress level in the pipe $\sigma_L$ 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,

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

# 5 DISCUSSION

# 6 REFERENCES

RSTRENG (1989), Kiefner, J.F. and Vieth, P.H., "A Modified Criterion for Evaluating the Remaining Strength of Corroded Pipe", Project PR 3-805, AGA

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