SKI Report 2005:03

Research

Probability of Detection for the Ultrasonic Technique according to the UT-01 Procedure

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January 2005

ISSN 1104–1374
ISRN SKI-R-05/03-SE

SKI perspective

Background

Models for Risk-Informed Inservice Inspection (RI-ISI) are today common and also proposed to be used in nuclear power plants in Sweden. SKI sees the needs and importance of building a model for determination of the probability of detection (POD) based on relevant data. Such a model can be used to evaluate the risk reduction of ISI in such RI-ISI models.

One way to obtain such information is to use data from qualifications, where the real NDT (non destructive testing) situation is imitated in a realistic way and where a quite large amount of data is available.

This project was set up to analyze data collected by the qualification body in Sweden. The data were recorded during 9 years of qualification of personnel for manual ultrasonic inspection following the qualified procedure called UT-01.

Purpose of the project

The main purpose of the project was to produce a model for POD of manual ultrasonic testing of data from a real testing situation. To make this possible the project has combined the knowledge and databank at the Swedish qualification body (SQC) together with competence in risk-studies and statistical methods.

Results

This study proposes a model for calculating the POD for manual ultrasonic techniques, based on qualification data in Sweden. The model analyses the qualification data statistically and combines a reduced number of data from real cracks with large number of data from simulated cracks in test pieces.

An important conclusion from the project is that the POD is strongly dependent on the absolute value of the crack depth. It is also concluded that adding variables such as wall thickness, will not improve the model.

This study also exemplifies how POD data can be used in risk informed ISI models.

Project information

Responsible for the project at SKI has been Peter Merck.
SKI reference: 14.43-011370/22259

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Probability of Detection for the Ultrasonic Technique according to the UT-01 Procedure

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January 2005

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Sammanfattning

SKI har finansierat ett forskningsprojekt som syftar till att ta fram data för provningseffektiviteten avseende att detektera sprickor, (engelska Probability of Detection, POD) med användning av ultraljudproceduren UT-01 för rör och komponenter. Sådan information behövs för riskinformerade kontrollprogram där POD används för att uppskatta den riskminskning som erhålls vid en provning. För ändamålet har används en kvalificeringsdatabas från SQC, Swedish Qualification Center. Data har bearbetats för olika tillverkade sprickor, IGSCC och utmattning i rostfria rör, under kvalificeringssituationer samt under olika MTO-förhållanden.
En relativt omfattande statistisk analys har genomförts där inflytande från olika varaiabler har undersökts. Projektet har givit följande observationer och slutsatser:

- POD är en stark funktion av det absoluta sprickdjupet a.
- Att addera flera variabler som t ex godstjocklek förbättrar inte modellen.
- Det är lättare att detektera en tillverkad utmattningsspricka än en spänningskorrosionsspricka.
- POD är högre under en kvalificeringssituation än under MTO-studierna.

Det visas i rapporten att POD bäst kan representeras av följande ekvation

$$POD = \Phi\left[0.1218 + 0.3720 \cdot \ln(a)\right]$$

där Φ är den normala fördelningsfunktionen. Det rekommenderas att denna ekvation används i riskinformerade kontrollprogram där UT-01 används som provningsprocedur.
I rapporten undersöks även hur stora riskminskningar man erhåller med olika antagna POD för rostfria rör med skademekanismen IGSCC med hjälp av ett datorprogram för riskinformerat provningsurval, kallat NURBIT. Det visas att med användning av den rekommenderade POD-funktionen från denna studie erhålls en något mindre riskminskning än vad tidigare POD-antaganden har givit.

Summary

In order to increase safety, in service inspections using NDT (Non Destructive Testing) are widely employed in nuclear power plants. RI-ISI (Risk Informed In Service Inspection) methods are used to optimize the NDT efforts. The POD (Probability Of Detection) of cracks in piping components is central for RI-ISI. Therefore the POD is of great interest in safety management.

The UT-01 procedure is used for inspections with ultrasonic technique in nuclear power plants in Sweden. As a part of the UT-01 procedure, inspectors must pass a qualification test held by the SQC (Swedish Qualification Centre).

Data from qualification tests and from MTO studies (Man Technology Organization studies performed after the qualification tests) are used in the present project to estimate the POD. The most important conclusions from the project are,

a) The POD is strongly dependent on the absolute value of the crack depth *a*.
b) Adding more variables to the model, for instance wall thickness, will not improve the model.
c) It is easier to detect a manufactured fatigue crack than a real IGSCC crack.
d) The POD is higher in the qualification tests than it in the MTO studies.

It is shown that the POD can be represented by the following formulation,

$$POD = \Phi\left[c_1 + c_2 \cdot \ln(a)\right], \qquad (1)$$

where Φ denotes the normalised Gaussian distribution.

The following POD for ultrasonic testing according to the UT-01 procedure is recommended,

$$\text{UT-SQC} \;\; POD = \Phi\left[0.1218 + 0.3720 \cdot \ln(a)\right]. \qquad (2)$$

The POD from Simonen & Woo is often used in RI-ISI analyses. This study indicates that their model, using model parameters corresponding to “UT-good”, overestimates the POD. The POD model recommended here results a lower probability of detection. The difference is largest for thin pipes.

The effect by using the different POD models in a RI-ISI analysis has also been investigated by using the RI-ISI analysis tool “NURBIT”.

1. Introduction

The study was supervised by Det Norske Veritas (DNV). A significant part of the study was done as a diploma work by Lina Tidström at the Department of Mathematics at the Uppsala University, supervised by Dr Sven Erick Alm. Björn Brickstad and Tomas Jelinek acted as advisors /1/. The study was financially supported by the Swedish Nuclear Power Inspectorate (SKI).

Due to increasing competition, financial pressure and safety demands, the so called risk informed methods are more frequently used today. The methods are used to estimate the risk level for a whole system, a subsystem, or some specific components. The results can be used to evaluate and optimize the risk mitigating actions. Both safety and economic hazards can be analyzed.

In the nuclear industry PSA (Probabilistic Safety Assessment) is widely applied. In a PSA-analysis, the conditional probability for core damage or radioactive release, $C = P(\text{core damage} \mid \text{leakage})$, can be estimated. The risk (core damage frequency) is calculated as the product of the conditioned probability and the frequency of leakage and rupture of a particular component.

To decrease the risk, the conditional probability can be decreased by adding extra safety systems, or increased reliability of the existing safety systems.

The other way to reduce the risk is to decrease the probability of leak or rupture of a component. This can be achieved through a number of ways:

- Repair, redesign or exchange of a component.
- Change of service conditions.
- Perform NDT inspections to find defects before they cause leakage or rupture.
- Install leak detection to discover leakage in an early stage before it challenges the safety systems.

Of the efforts above, performing non-destructive testing (NDT) gives a good opportunity to reduce the probability of leakage or rupture. If a defect is detected, either the component will be repaired, or the defect will be subjected to continuous monitoring. In this manner, the defect in the component will not cause any leakage or rupture. As a result, the risk is reduced.

In an RI-ISI analysis, the probability of leak and rupture at a particular component can be calculated by using the theory of Probabilistic Fracture Mechanics (PFM). In such an analysis, the effect of inspection can be taken into account. Therefore, the reliability of the POD (Probability Of Detection) for different inspection techniques is important.

1.1 Earlier POD Results

It is common to define a POD as

$$POD = \Phi\left[c_1 + c_2 \cdot \ln(a/h)\right] , \qquad (3)$$

where a is the crack depth, h the wall thickness and Φ the Gaussian distribution function. The variable in Eqn. (3) is the relative crack depth a/h. In a study by Simonen and Woo on Round Robin-trials /2/, three different POD equations, concerning the detection ability of different testing teams, have been defined,

$$POD = \begin{cases} \Phi(0.240 + 1.485 \cdot \ln(a/h)) & \textit{for a poor team} \\ \Phi(1.526 + 0.533 \cdot \ln(a/h)) & \textit{for a good team} \\ \Phi(3.630 + 1.106 \cdot \ln(a/h)) & \textit{for an advanced team} \end{cases} . \qquad (4)$$

The results of POD by different teams are shown in Fig. 1. The POD for "good team" is better than the average teams. The "advanced team" represents a team whose performance may be achieved with further improved procedures.

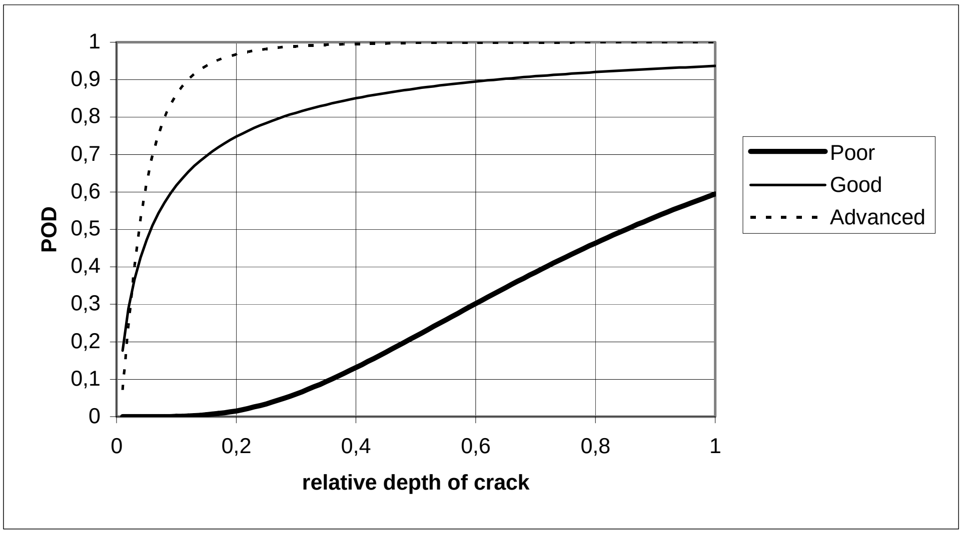

Fig.1 POD from the study by Simonen & Woo /2/.

Based on the data from the PISC III exercise, Simola and Pulkkinen /3/ established the following equation:

$$POD = \Phi(1.64 + 0.75 \cdot \ln(a/h)). \qquad (5)$$

The result of Eqn. (5) is plotted in Fig. 2. It is quite near the study in /2/ using good team data.

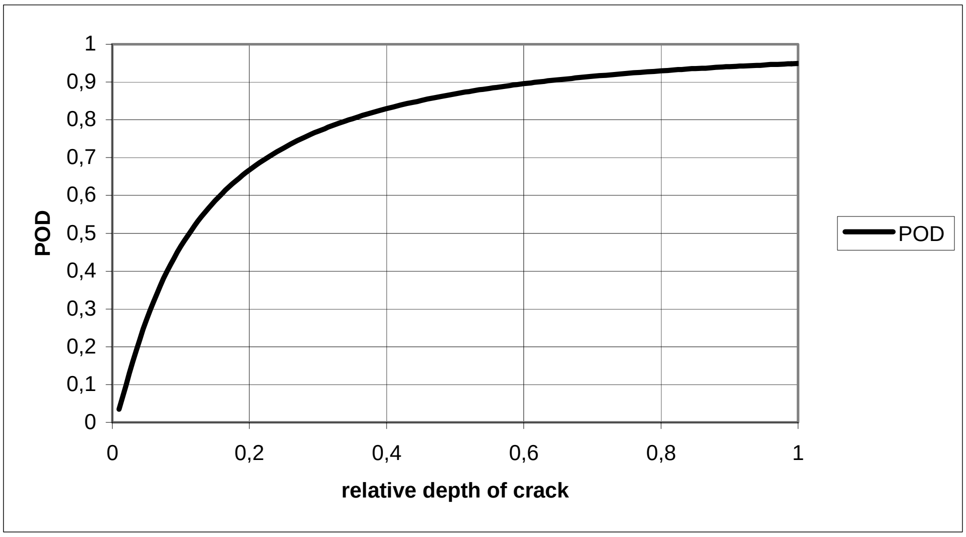

Fig. 2. The study by Simola & Pulkkinen /3/.

1.2 Objectives of the project

The objectives of the project are:

1. To make a statistical analysis of qualification data and MTO-data used for qualification of inspection engineers in Sweden for the inspection procedure denoted UT-01 which uses an ultrasonic technique to detect stress corrosion cracks in stainless steel pipes.
2. From the statistical analysis, to determine a best estimate POD-curve with confidence bands.
3. To analyse the parameters which influence the level and shape of the POD-curve the most.
4. To determine the risk reduction from inspections in a typical Risk-Informed ISI analysis using the POD-curve from the study.

1.3 Data from Qualification tests

In Sweden, inspections to nuclear facilities must follow a specified procedure. If the ultrasonic technique for stress corrosion cracks in austenitic stainless steel piping is employed, the so called UT-01 procedure should be used. As a part of UT-01 procedure, all inspectors have to pass a qualification test. A detailed description of the qualification test is provided in Section 2.5.

If an inspector fails the qualification, she/he will not be allowed to perform the inspection of nuclear facilities. Therefore the inspectors are subjected to a certain pressure during the qualification. This will probably influence their test results, and their performance in the test may not be exactly comparable to their performance during a real inspection.

1.4 Data from MTO test

After the qualification test, another inspection test, an MTO test, was performed. The ultrasonic technique was employed. The purpose of the MTO test was to closely study the factors which affects the reliability of the inspection. A detailed description of the MTO test is provided in Section 2.6

All the inspectors who performed the MTO test were qualified from the qualification test. Heat and noise were added during the test to simulate the real environment in a nuclear plant. Since the inspectors had no requirement on achieving a specific result for "passing" the test, they were not subjected to pressure. Therefore the inspection result from the MTO test may be different than the result from qualification tests.

2 Background Information

2.1 Test blocks

The coordinate system shown in Figure 3 is used to characterize the cracks in the test blocks. All test blocks were made of austenitic stainless steel piping.

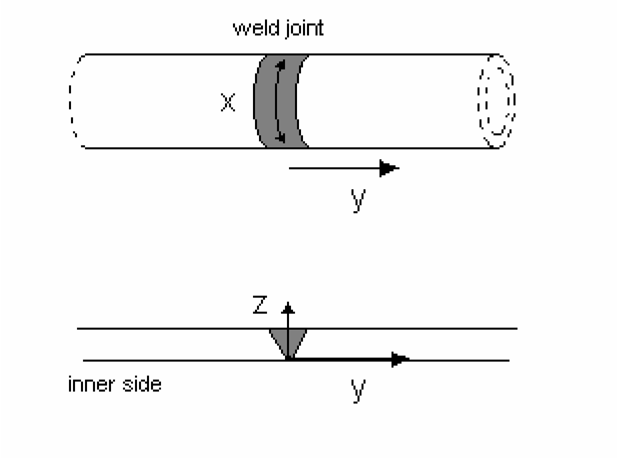

Fig. 3. Coordinate system

The following parameters are used to characterize the cracks:

- Crack depth (measured from the inside of the pipe in the z direction).
- Crack length (for a circumferential crack is the distance in the x direction).
- Wall thickness.
- Distance from weld.
- Crack tilt (the angle between a crack and the z-axis, see Fig. 4).
- Crack skew (the angle between crack and weld (x-axis), see Fig. 4).
- Cold-Deformed Elbow (CDE; a test block is formed as a bent pipe with cracks).
- IGSCC (a kind of service induced defect. A test block is a piece of pipe from a nuclear power plant which contains real IGSCC cracks).
- Heat Affected Zone (HAZ; is an area between the weld fusion line and the base metal. IGSCC cracks are usually located at the austenitic stainless steel weld HAZ).

The unit of mm and degrees are used during the tests.

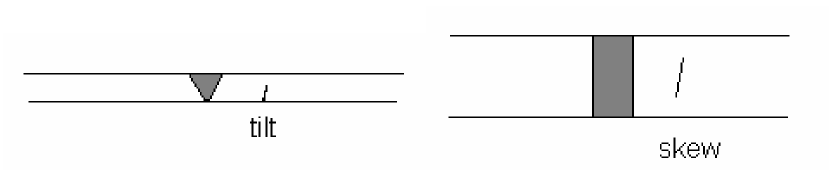

Figure. 4. Crack tilt and skew

2.2 Cracks in the test blocks

In total there are 117 cracks in the test blocks with crack depths between 2 and 26 mm, crack lengths 12-66 mm and distance to weld 3-22 mm. The wall thickness of the test block is in between 4 and 35 mm. Most of the cracks were manufactured by fatigue and then welded into the test blocks. There were 14 real IGSCC cracks in straight pipes which were taken from the nuclear power plants. The crack depth and length distribution of all cracks are shown in Fig. 5, and the distribution of the distance between the crack and the weld is shown in Fig. 6.

It is observed that there is one very long crack. The crack depth of this long crack is zero. This crack is shown with a square symbol in Fig. 5 and was not considered in the estimation of POD. There were three other cracks which were never used in the test and also removed from the estimation.

There are 16 cracks in CDEs, which are shown as circular symbols in Fig. 6. Earlier experience has shown that the probability for IGSCC cracks initiating in CDEs can be very high. Almost all these CDEs have been removed from Swedish nuclear power plants. Therefore the cracks in CDEs were excluded from the estimation. As a result, a total of 97 cracks were used for the estimation of the POD function.

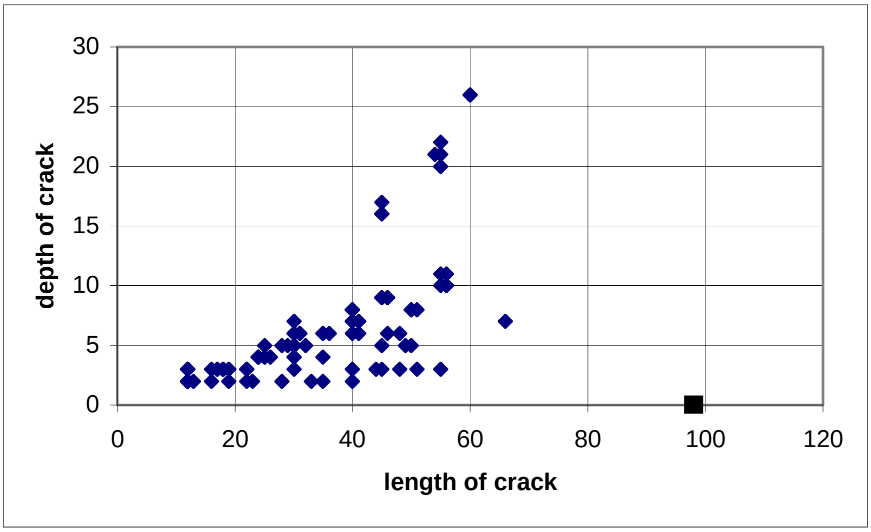

Fig.5. *Depth [mm] plotted against length [mm], for all 117 cracks, the crack without depth is symbolised with a square.*

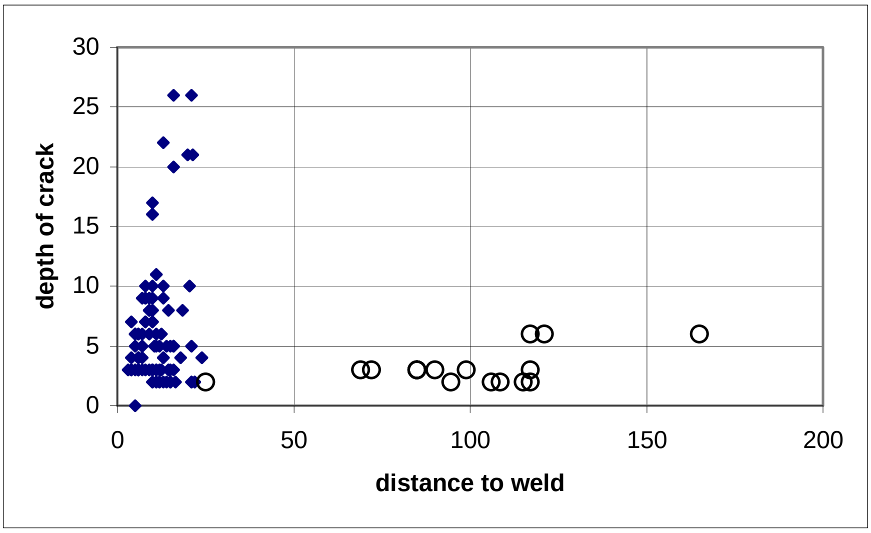

Fig.6. *Depth [mm] plotted against distance to weld [mm], for all 117 cracks, cracks from Cold-Deformed Elbow (CDE) are symbolised with circles.*

2.3 Correlation between crack depth and other variables

The dependence between the variables in pairs can be calculated with the so-called correlation coefficient, *r*. When the correlation is zero between two variables they are uncorrelated, (*i.e.* there is no dependence). A positive correlation indicates that a large value for one of the variables means a large value for the other as well. A negative correlation indicates the opposite. The magnitude of *r* is bounded by ±1.

Correlations between the variables crack depth, crack length, distance to weld and thickness of pipe for the 97 cracks are shown in Table 1. The results in Table 1 are obtained using the statistical software SAS /16/. In the lower part of each cell the *p*-value for the hypothesis test: correlation = 0, is displayed. A *p*-value less than or equal to 0.05 means that the hypothesis is probably not correct, and that there is some dependence between the variables, *i.e.* that the variables presumably are dependent in some way. Variables are more likely to be correlated the smaller the *p*-value is.

Table 1. Correlation coefficient, r (upper value), and p-values (lower value) for the 97 cracks considered for estimation of POD.

	depth	length	thickness	distance
depth	1			
length	0.7 <.0001	1		
thickness	0.6565 <.0001	0.45821 <.0001	1	
distance	0.23145 0.0225	0.10362 0.3125	-0.06882 0.5030	1

The 12 real IGSCC are not more than 8 mm deep, between 28 and 66 mm long, located at 10-21 mm distance from a weld in pipes with a thickness of 10 or 16 mm.

The 12 cracks in the MTO study have depths in the interval 2-8 mm, lengths 12-66 mm, they all belong to thickness group 2, with 7-11 mm thick pipes and located 4-19 mm from a weld.

The information obtained from Table 1 (strong correlations between: crack depth and crack length; crack depth and wall thickness; crack length and wall thickness) is used in section 3.6 as additional information to include relevant variables in an estimated POD function.

2.4 Variables affecting the POD

The variables mentioned above (Section 2.1) and the interactions between these variables will influence the resulting POD. Usually, the relative crack depth (crack depth divided by wall thickness) is commonly used in a POD model. This implies that the probability of detection is different for cracks with the same absolute depth but present in pipes with different wall thickness.

The distance between the ultrasonic transmitter and the crack may affect the detection. Cracks of the same relative depth may have very different absolute depths and different distance to the transmitters. Therefore it may be better to have a POD model which is related to the actual crack size.

Crack length may also give information on the detection of the crack. Intuitively, depth is more interesting, since it is more closely related to the probability of leakage. The interaction between the crack length and depth will also be considered.

The distance between the defect and the welded joint is not expected to influence the POD to a great extent. If a crack is very close to a weld, the operator may have difficulties to distinguish the signals reflected from the crack and from the weld boundary.

If the direction of the reflected waves has a small angle to the transmitters, the operator may have difficulty to detect the crack. It is because the waves are reflected in another direction instead of to the transmitter. This problem may arise by presence of crack *tilt* or *skew*. In the qualification tests and MTO tests, cracks with tilt ±30° and skew ±20° are included.

2.5 Qualification tests in SQC

It is well known that the operators' skill has a crucial effect on the reliability of a NDT test. As a part of the UT-01 procedure /4/, all operators must pass the qualification examination before they can perform inspections in nuclear power plants. The operator must demonstrate his skills to calibrate the equipment, to detect, and to characterize cracks. The qualification tests have been performed at the Swedish Qualification Centre /7/ (SQC) since 1998/1999.

The data contain detection results from 41 people who had performed qualification tests at SQC. During the tests, 27 inspectors passed during the first try. 13 inspectors made a second try, 8 of them qualified. One person made a successful third try. Among the 41 inspectors, five of them had never been qualified. All together there are results from 55 different test cases.

2.5.1 Group of test blocks

Depending on the wall thickness of the pipe, the test blocks are divided into three different groups,

Group 1: wall thickness <7 mm,
Group 2: wall thickness 7-15 mm,
Group 3: wall thickness >15 mm.

Each group contains 4-12 cracks which are unevenly distributed in each test block. Some test blocks have no cracks at all.

2.5.2 Qualification procedure

A qualification will take about 5-7 days. Several test blocks containing about 20 cracks in different groups will be examined. Usually only 2-3 test blocks will be tested each day. In order to make the test environment as realistic as possible, the test blocks were mounted at different heights in different angles.

Usually there are 6-8 transmitters which will be used in the examination. Only one of these transmitters is required to be calibrated in the field and rest of them can be calibrated in advance.

2.5.3 Requirements of qualification

In order to characterize the examination, a hit box is defined for each defect. The hit box is surrounding the true crack by ±10 mm. A crack is considered correctly detected and characterized if it reported as a crack and more than 50% of the detected crack is within the hit box. The tolerance for the measured crack length is ±20 mm and for the measured crack depth is ±2 mm for wall thicknesses ≤15 mm and ±3 mm for wall thicknesses >15 mm..

The following criteria are used to judge the qualification,

1. At least 70% of the cracks for an individual test series should be correctly detected and characterized.
2. At least 80% of all defects in all test series should be correctly detected and characterized.
3. A low percentage of false calls.

If the operator fails the qualification, he can have another try after one month. In the re-qualification test, the operator is tested only on the test blocks which he failed on the first time. If he fails the re-qualification test, a new full scale qualification test can be arranged after one year.

It is required that the operator is active in NDT inspection and have to perform a repeating examination every fifth year.

2.6 Man-Technology-Organization (MTO) test

Operators performing NDT have to have a high concentration level during the inspection. Noise, heat, small space to move around, individual decision-making, long working hours and limited time available are stress factors which will affect the performance. The ability to perform well under pressure is different from operator to operator. Even though the same equipment and procedures are used in the inspection, different operators may produce different detection results. In addition, the same operator may perform differently at different occasions.

It is known from international studies that operators may perform differently during a qualification test compared to a real situation. At a qualification test, cracks are expected. In nuclear power plants, however, the probability of cracks is very low. In most cases, small indications are due to material imperfections. The operators may probably not pay much attention to these small indications and thus miss the small cracks in a real case. Therefore, a POD estimated from qualification tests may probably overestimate the true detection probabilities for small-size cracks.

In order to study the psychological aspects, two extra studies /5/ and /6/ were performed at the Stockholm University. The ultrasonic technique was used. The operators in these studies were all qualified in the earlier qualification tests.

The test blocks used in the MTO test were taken from qualification tests. In the first study, 14 operators inspected test blocks which contained 9 cracks. In the second study, 19 operators performed inspection of test blocks which contained 12 cracks. Among these cracks, 9 cracks were used in both studies and 12 operators participated at both occasions. Two cracks were real IGSCC cracks (one IGSCC crack in the first study and two IGSCC cracks in the second). The interval between the two studies was one year.

2.7 Characterisation of test results

The inspection results from the qualification test and MTO test form a base for the present study. These data were coded anonymous for both cracks and the operators who performed the tests. In the estimation of the POD, four different detection alternatives are defined concerning the detection and the characterization of the cracks during the inspections, see Table 2.

Table 2. Detection alternatives.

X	Correct; *i.e.* the inspector has identified the crack and reported a crack size and location close enough to the real crack,
FC	False Call; the inspector detected a crack where there is no crack,
0	Wrong; an existing crack has not been detected,
	No test; the piece containing a crack has not been examined,
0F	Detection but incorrect characterisation. For example a crack was detected but incorrectly characterized (size, location) or a defect was detected, but incorrect characterized as a geometrical defect instead of a crack.

Only correct detection (X) is considered as a successful test result. False call (FC), incorrect characterisation (0F) and wrong detection (0) are considered as unsuccessful test results.

2.8 Comments on qualification and MTO data

Some persons have performed qualification tests twice (one person even three times) and also participated in one or two MTO-studies. One approach is to consider them as different persons at different occasions, since their knowledge and skill have been improved after each performance. In addition, some operator may inspect the same test blocks several times during the qualification tests.

Nine test occasions were removed from data since these (five) persons never qualified. These persons will not be allowed to perform UT inspection according to the requirements for the UT-01 procedure in nuclear power plants.

The qualification data is sparse with only 3-9 tests per crack. This fact will make inferences uncertain. The cracks tested in the MTO studies will have been inspected 19 to 33 times.

3 Estimation of POD

3.1 POD Model

3.1.1 Distributions

There are only two possible outcomes when searching for a crack: either it is correctly detected or not. The detection alternative *X* in Table 2 is defined as detected cases and the other alternatives as undetected cases. The result can be described with a stochastic variable $W_{i,k}$, following the Bernoulli distribution:

$$W_{i,k} = Be(p_i)_{test\ k} = \begin{cases} 1, & \text{for detection alternative } X \\ 0, & \text{for other detection alternatives } FC,\ 0,\ 0F \end{cases} , \quad (6)$$

With

$$\begin{cases} p_i = P(W_{i,k} = 1) \\ i = \text{crack } (1,\ldots,N) \\ N = \text{total number of cracks} \\ k = \text{test } (1,\ldots,n_i) \text{ of crack } i \\ n_i = \text{total number of tests of crack } i \end{cases} \quad (7)$$

The binomially distributed variable Y_i can be obtained by a summation of $W_{i,k}$ for crack *i*,

$$Y_i = \sum_{k=1}^{n_i} W_{i,k} \ , \quad (8)$$

Therefore Y_i can be expressed as,

$$Y_i \sim \mathrm{Bin}(n_i, p_i) \ , \qquad (9)$$

with,

$$\begin{cases} E(Y_i) = n_i \cdot p_i \\ \mathrm{Var}(Y_i) = n_i \cdot p_i \cdot (1 - p_i) \end{cases} \qquad (10)$$

The probability of correct detection, p_i, is unknown but can be estimated by the observed relative detection frequency: $\hat{p}_i = y_i / n_i$, where y_i is the observed detection frequency. p_i depends on which crack is being tested and its specific size, and more correctly expressed as a function of $\boldsymbol{x}_i$ as,

$$p_i = p(\boldsymbol{x}_i) \ , \qquad (11)$$

where $\boldsymbol{x}_i$ is a variable vector for crack size and location,

$$\mathrm{E}(\hat{p}(\boldsymbol{x}_i)) = p(\boldsymbol{x}_i) \, , \qquad (12)$$

and

$$\mathrm{Var}(\hat{p}(\boldsymbol{x}_i)) = \frac{p(\boldsymbol{x}_i) \cdot (1 - p(\boldsymbol{x}_i))}{n_i} \, . \qquad (13)$$

Since the operators skill will affect detection, $\hat{p}(\boldsymbol{x}_i)$ depends on the individual operator. In the present analysis, the difference between the operators is not considered. Since only the test data by qualified operators are used in the estimation, it is expected that the difference of the test results due to different operators is limited. Nevertheless, the difference between operators will cause some problems when making inference for the POD, which is discussed in Section 3.1.3.

3.1.2 Generalized linear models (GLIM)

To examine how POD depends on crack size and location, a regression analysis is performed according to generalized linear models. This is appropriate for the binomial distribution.

The event probability p (actually, the response of the mean) and the explaining variables $x_1, x_2, \ldots, x_{R-1}$ are related by a so-called link function g,

$$g(p) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_{R-1} x_{R-1} = \mathbf{X}\boldsymbol{\beta}. \qquad (14)$$

For the Binomial distribution the so-called probit and logit links are commonly used. Detailed information about GLIM and statistical theory are presented in Appendix A.

3.1.3 Overdispersion

The detection probability does not only depend on the size and location of the crack, but also depends on the performance of the operators. One way to make the human factor less influential is to develop procedures and strategies and educate personnel. If a model for POD considers only the sizes of the cracks, the results will be affected by some underlying distribution for the detection probabilities over individuals. The variance of the response will be larger than it would be expected for binomially distributed variables resulting in too many significant parameters. A way to model overdispersion is to introduce a so-called scale parameter, ϕ, into the variance function $\mathrm{Var}(Y) = \phi \cdot \sigma^2$. The estimation of the model parameters will be the same as it is without a scale parameter. Only the standard deviation will change and affect their significance. There are different ways to estimate the parameter ϕ. One of them is the so called Williams method (available in the statistical software SAS /16/, Statistical Analysis System). Since POD model will not to be used for prediction of detection probabilities for different individuals, there is no need to perform a more exact analysis for overdispersion. The Williams method will be accurate enough.

3.2 POD estimation

The cracks in the test blocks are fatigue cracks and IGSCC cracks. Since the available data is very limited, all data except data from the unqualified operators have been used.

Before fitting a POD model, the following questions should be answered:

- Should all the data from the qualification tests and MTO-studies be used?
- Which kinds of cracks should be included?
- Which link function is appropriate?
- Should the variables be transformed?

The qualification tests and MTO test data contain the following information: crack depth, crack length, distance between the crack and the weld, thickness of pipe, crack tilt and skew, IGSCC, HAZ or CDE, and detection alternatives.

The examined variables were:

- crack depth
- crack length
- distance
- wall thickness
- interaction of second order of the variables above
- indicator variable for tilt,
- indicator variable for skew

- indicator variable for IGSCC
- indicator variable for MTO
- absolute depth *a* of crack

The parameter IGSCC and MTO are defined as indicator,

$$IGSCC = \begin{cases} 1, \; IGSCC \; crack \\ 0, \; Fatigue \;\; Crack \end{cases}, \tag{15}$$

and

$$MTO = \begin{cases} 1 & \text{, for cracks tested in the MTO studies} \\ 0 & \text{, otherwise} \end{cases}. \tag{16}$$

The result was a large model with many significant explaining variables, for example, crack depth, crack length, wall thickness, distance between the crack and the weld, interactions: (depth×length), (depth×distance), (thickness×distance), skew, MTO and IGSCC. The reason for this is probably overdispersion, see Section 3.1.3. This is supported by the deviance statistics (D = 145.9545 with 87 degrees of freedom, the ratio should be close to one).

To avoid misleading results due to inference of the regression parameters, a scale parameter to handle the overdispersion was estimated by Williams method. Based on the large model, the procedure eliminating non-significant parameters was carried out once more.

A 14-parameter model was established with probit link. Step-by-step the most insignificant (5% significance level) variables were removed. Finally it was found out that crack depth, crack length and wall thickness, together with the indicators IGSCC and MTO, are strongly significant. Referring to Table 1, there are strong correlations between crack length and thickness with crack depth. The combination of three size variables or interactions does not improve the model significantly. Therefore, only the crack depth was included. Also, it was found that using the relative crack depth *a/h* will give a worse correlation., see Fig. 7.

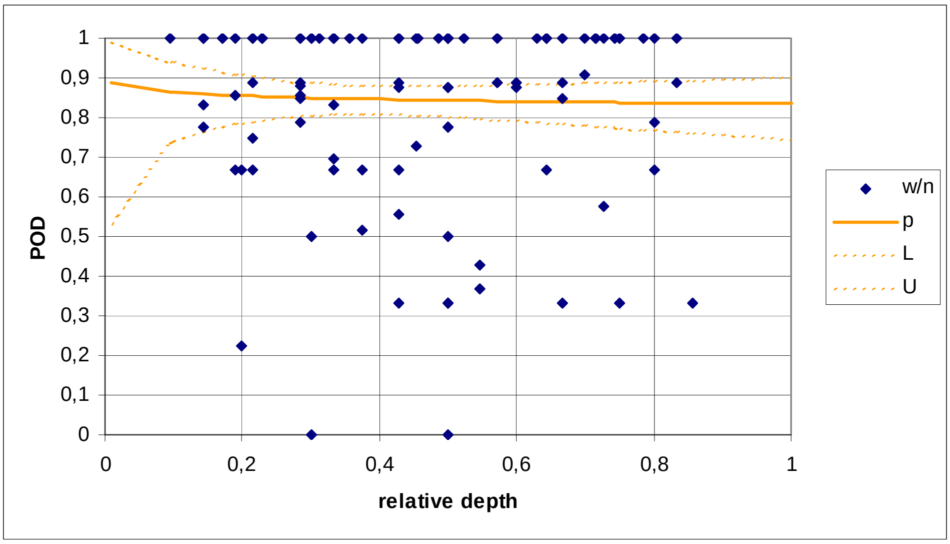

Fig. 7. POD as function of crack depth normalised with the wall thickness. All data is used.

The indicators of tilt and skew are non-significant if they are added to the model. Since the logarithm of the crack depth is used, Eqn. (17), the POD will approach zero for very small crack depths, i.e. a non-existing crack cannot be found.

Thus the POD function can be written as

$$POD = \Phi(c_1 + c_2 \cdot \ln(a) + c_3 \cdot IGSCC + c_4 \cdot MTO), \qquad (17)$$

4 Results of POD

4.1 POD under different conditions

Based on the data from both qualification tests and MTO tests, the following model for the POD can be obtained,

$$POD = \Phi(0.6503 + 0.3720 \cdot \ln(a) - 0.5285 \cdot IGSCC - 0.5015 \cdot MTO). \qquad (18)$$

Significant and negative parameters are obtained for both the IGSCC and MTO indicator. This indicates that,

a) IGSCC cracks are more difficult to detect than fatigue cracks.
b) Detections in the qualification tests were better in comparison with the detection in the MTO tests.

In order to establish Eqn. (18), it is assumed that POD follows the same model form, c_2 is 0.3720 ln(a) for all cases; fatigue and IGSCC cracks, MTO and qualification tests. This assumption may be questioned. Whether the effects of IGSCC and MTO are additive is uncertain, since there is only two IGSCC cracks being tested both at qualifications and MTO. This will make inference of IGSCC-MTO-interaction uninformative. IGSCC and MTO are treated as separate variables, and the POD is lower for both IGSCC and MTO.

If only IGSCC cracks in qualification tests are considered, then IGSCC = 1 and MTO = 0, and the POD is,

$$POD = \Phi(0.1218 + 0.3720 \cdot \ln(a)). \qquad (19)$$

If only fatigue cracks in MTO tests are considered, then IGSCC = 0 and MTO = 1, and the POD is,

$$POD = \Phi(0.1488 + 0.3720 \cdot \ln(a)). \qquad (20)$$

Finally, if only fatigue cracks in qualification tests are considered, then IGSCC = 0 and MTO = 0, and the POD is

$$POD = \Phi(0.6503 + 0.3720 \cdot \ln(a)). \qquad (21)$$

The results of POD based on Eqns. (19)-(21) are plotted in Fig. 8.

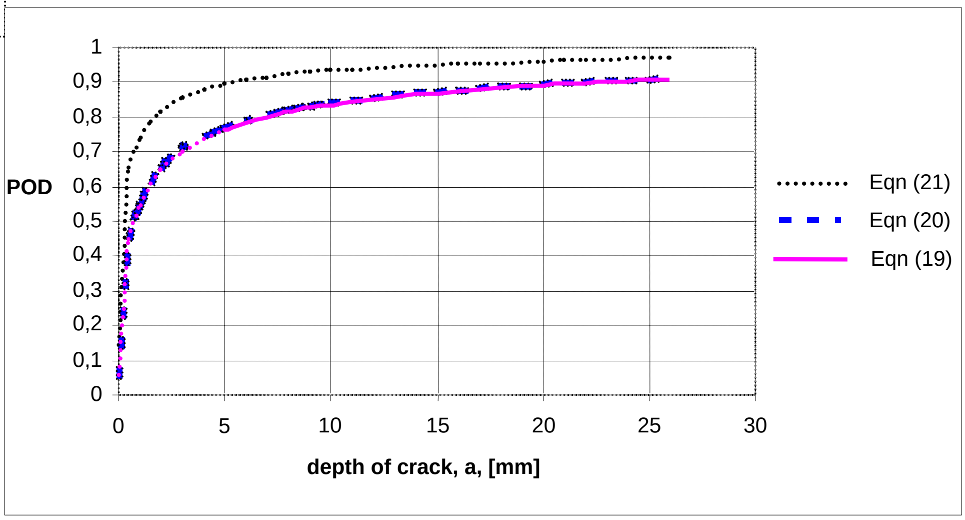

Fig. 8. POD for different cases.

In Figs. 8-11 the POD curves are plotted separately, together with observed relative detection frequencies (y/n) and lower and upper bands (95% confidence). The confidence band connects the confidence intervals for each point on the curve.

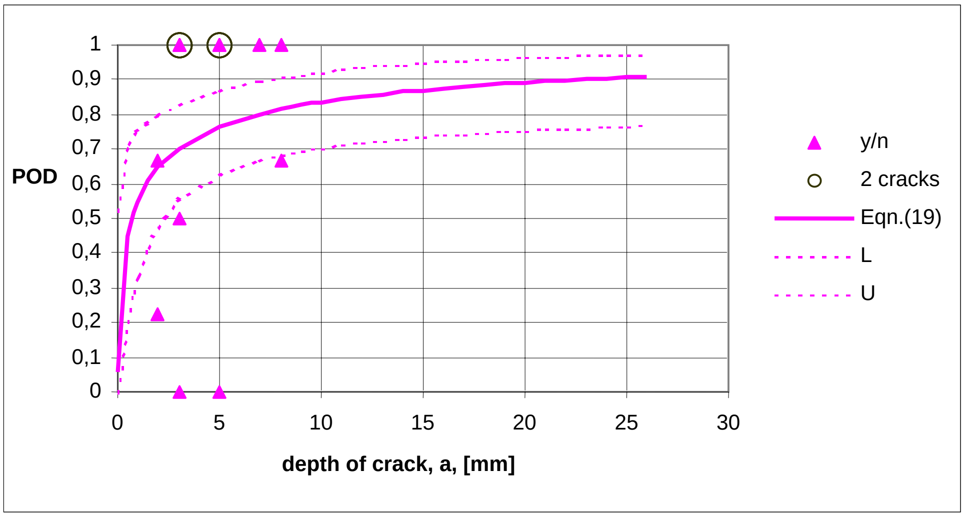

Fig. 9. POD for IGSCC cracks in qualification tests, Eqn. (19). Two cracks with the same depth and the same detection frequencies are encircled.

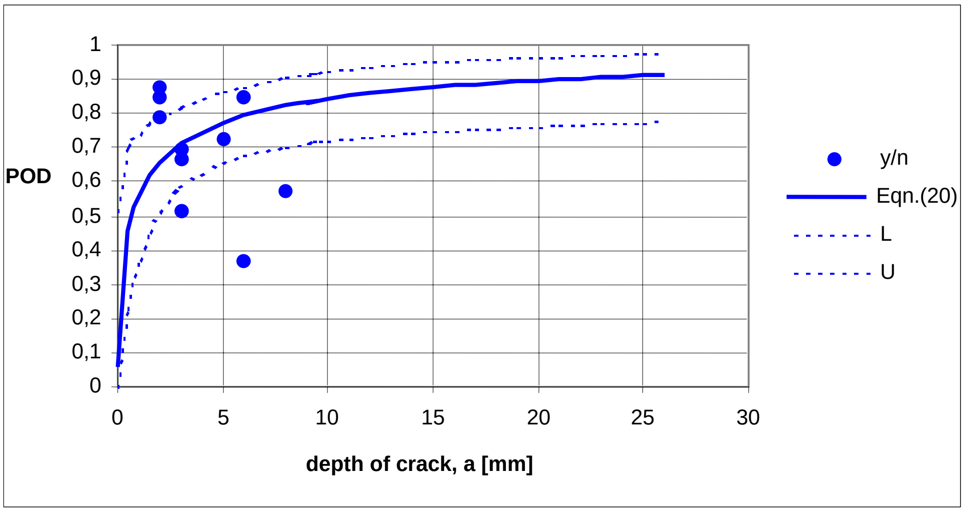

Fig. 10. POD for fatigue cracks in MTO study, Eqn. (20).

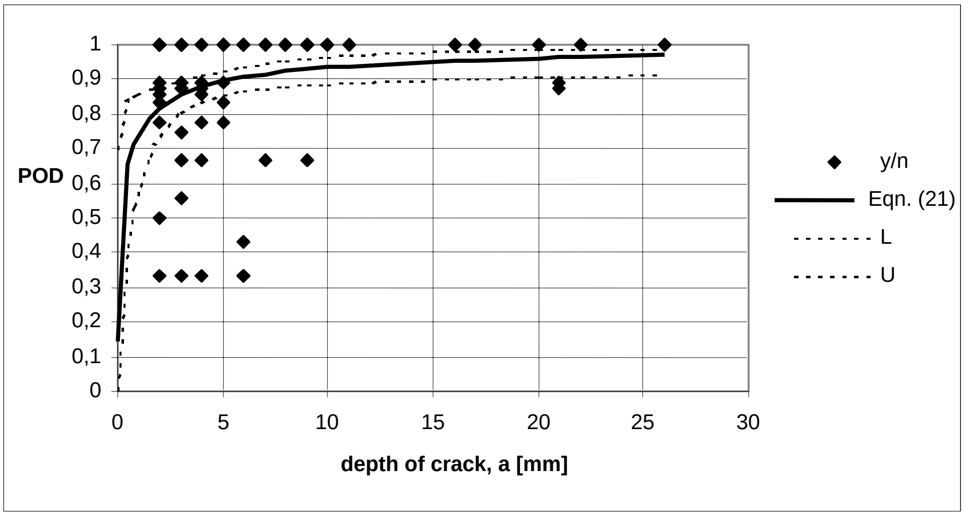

Fig. 11. POD for fatigue cracks in qualification tests, Eqn. (21).

It is judged that Eqn. (22) will give the best representation of POD in a true inspection situation in a nuclear power plant in Sweden by the UT-01 procedure:

$$\text{UT-SQC:}\quad POD = \Phi(0.1218 + 0.3720 \cdot \ln(a)), \qquad (22)$$

The POD level of the curve represented by Eqn. (22) is based on service induced defects (authentic IGSCC cracks) and will be used in Section 5. However, note that data points from all cracks are used to determine the shape of the curve represented by Eqn. (22).

4.2 Discussion

There are only 12 real IGSCC cracks in the qualification tests. In addition, the total number of cracks in MTO tests is also 12. The data set based on either IGSCC cracks or MTO tests are too small to form a appropriate data base for a statistical analysis. Therefore the use of all 97 cracks is necessary for the POD estimation.

It is assumed that the model shape is the same (same c_2) for both fatigue and IGSCC cracks in both qualification and MTO tests. The POD level, c_1, was lowered to represent the IGSCC cracks. Almost the same c_1 is obtained if the level is adjusted to the MTO data. Whether the effects of IGSCC and MTO are additive (c_1 is lowered both for IGSCC and MTO) is uncertain, since there were only two IGSCC cracks being tested both at qualifications and MTO studies.

There are other uncertainties in the estimated POD,

- Most of the cracks in the tests were manufactured fatigue cracks.
- The inspections were performed in a laboratory environment, although measures were taken to simulate the real environment.
- Data from real IGSCC and MTO studies were sparse.
- IGSCC and cracks tested at MTO studies have depths less than or equal to 8 mm.
- The assumption that detection probabilities in an MTO situation have the same model as detection probabilities in a qualification situation may be questioned.

It would be interesting to further explore the different crack morphology between the fatigue cracks and IGSCC which may give hints to the reasons behind the somewhat lower detection rate for the IGSCC cases. Also, it would be worth to further investigate the MTO aspect of the inspections.

5 Risk reduction factors using different POD-curves

5.1 Risk reduction

In this section, two pipe welds are considered for which there is a potential for a stress corrosion crack to develop which eventually may grow to leak or break if it remains undetected. One way of reducing the failure probability and the risk of core damage for a pipe is to use inspections with a sufficient efficiency and inspection interval. It is here assumed that UT-inspections are performed having a Probability of Detection (POD) which only depends on the crack depth a, or possibly on the normalised crack depth divided by the wall thickness h.

For the two pipes, an evaluation of the core damage frequency will be performed and the established POD from this investigation will be used for different inspection intervals Δt, to find out the risk reduction and also compared with previously used POD-curves.

For the risk evaluations, the RBI-code NURBIT /8/ is used. NURBIT is a software developed for selecting an appropriate inspection programme in Nuclear piping systems which have stress corrosion as the dominating damage mechanism.

The first pipe is a stainless steel pipe with an outside diameter 114.3 mm and a wall thickness of 8 mm. The second pipe is a stainless steel pipe with an outside diameter 230 mm and a wall thickness of 21.5 mm. The damage mechanism is IGSCC with the potential of circumferential cracks to initiate and grow in the HAZ of the girth welds. Appendix B gives a summary of the input data for these welds used in NURBIT. The inspection data for this weld is given in Table 3. The time of evaluation of the risk for core damage is 2000 and end of operation is assumed to be 2015. The year of start of operation is 1975.

Table 3. Inspection data for the risk reduction study.

Year of inspection	**Inspection method**
1975	UT-poor
1985	UT-poor
1995	UT-poor
2001	User-defined POD
2001 + Δt	User-defined POD
2001 + $2\Delta t$	User-defined POD
etc.	User-defined POD

The POD-curve denoted “poor” is described in /8/ and shown in Fig. 12. It essentially implies very little benefit of an inspection. From 2001, more efficient inspections are used (reflecting an assumed start of qualified inspections), denoted “User-defined

POD”. Here two sets of user-defined POD will be compared:

$$\text{UT-good: } POD = \Phi[1.526 + 0.533 \cdot \ln(a/h)] \tag{23}$$

$$\text{UT-SQC: } POD = \Phi[0.1218 + 0.372 \cdot \ln(a)] \tag{24}$$

Here Φ denotes the normalised Gaussian distribution function. The UT-SQC curve is used here as a recommended curve for future risk evaluations when the procedure UT-01 is used in Sweden for qualified inspections of stainless steel pipes. It is based upon all the 97 defects in the SQC database for UT-01 (except from the cold-deformed elbows), where the 12 real IGSCC defects are used to adjust the level of the curve as described earlier. Note also that in Eqn. (24), POD is formulated as function of the absolute crack depth. In contrast, POD in Eqn. (23) is formulated as function of the normalised crack depth. This means that the comparisons between Eqn. (23) and (24) will be different for different pipe wall thicknesses (see Fig. 13 and 14). One reason for the SQC database results being insensitive to the normalised crack depth is that for near side defects, the UT beam only passes through parent material so the attenuation of the beam will be low. This means that an absolute crack depth in a thick pipe should be equally easy to detect as the same absolute crack located in a thin pipe.

Note also that the POD defined in (23) and (24) is defined for surface cracks only. If an undetected through-wall crack in the pipe is subjected to an inspection, it is assumed here that this through-wall crack is detected with the probability of 1.0.

Fig. 12 shows the POD as function of the normalised crack depth, which is a form often presented in international studies.

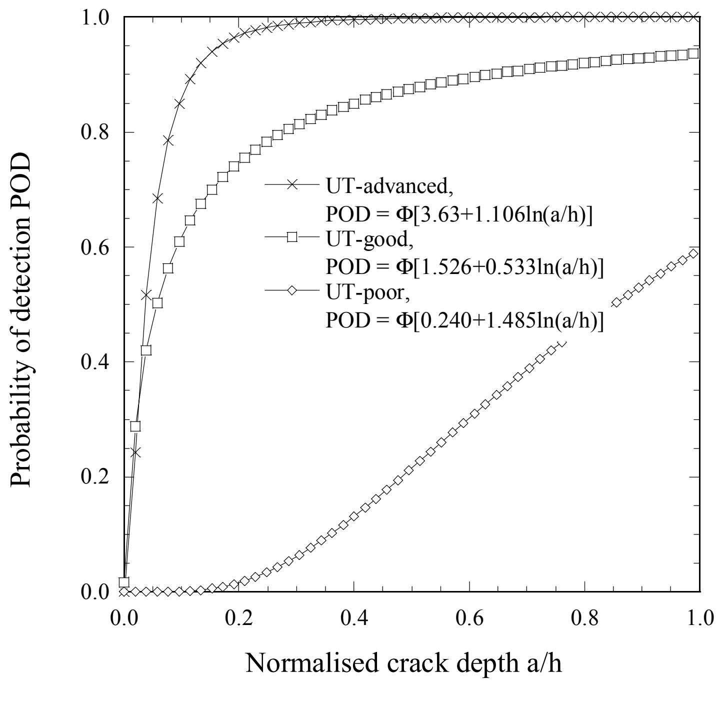

Fig. 12. POD as function of normalised crack depth.

The relation for the POD in Fig. 12 has been taken from a study by Simonen and Woo /2/ for the case of inspection of stainless steel pipes with access from the same side of the weld as where the potential crack is located. The term ”UT-poor” represents a lower bound performance among the teams that participated in programs to assess inspection efficiency (*cf.* Doctor *et al.* /13/). ”UT-good” represents a team with over average performance in round robin trials that have been conducted and ”UT-advanced” represents a performance that may be achieved with further improved procedures. For qualified inspection procedures used in Sweden for IGSCC in stainless steels, the coefficients corresponding to ”UT-good” has been assumed until now. For example, this has been used by Brickstad /14/ in the pilot study of Oskarshamn, unit 1. Non-qualified inspections may correspond to “UT-poor” inspections.

Figure 13 and 14 shows a comparison between Eqn. (23) and (24) for the two considered pipes where POD is plotted versus absolute crack depth. It is observed that the UT-good curve, Eqn. (23) is slightly higher than the SQC-curve, Eqn. (24). The difference is larger for the thin pipe compared to the thick pipe.

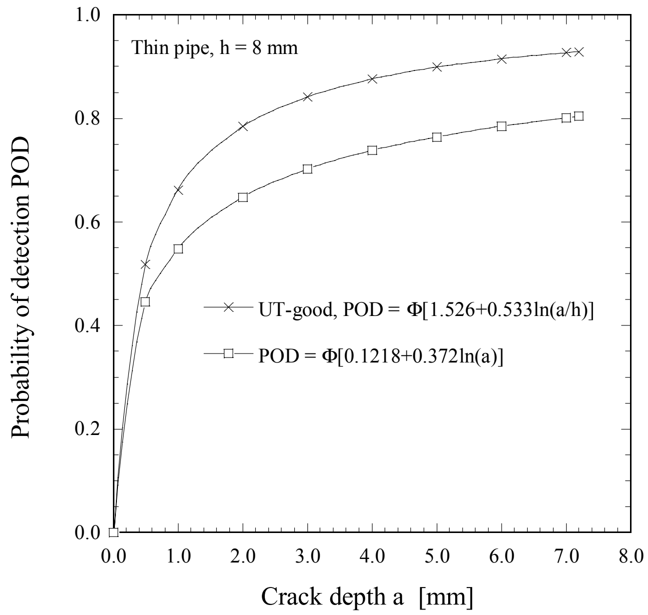

Fig. 13. Comparison of POD for a thin pipe.

When analysing the welds using NURBIT, the following definition of the risk reduction factor *RRF* is used:

$$RRF = \frac{\text{CDF(no ISI)}}{\text{CDF(with ISI using inspection interval } \Delta t)} \tag{25}$$

$$CDF = P(smallleak)\cdot C(smallleak) + P(largeleak)\cdot C(largeleak) + P(rupture)\cdot C(rupture) \tag{26}$$

CDF is the core damage frequency, defined in Eqn. (26), where P is the failure frequency (per year) and C is the consequence (or rather the conditional core damage probability give a pipe failure, also denoted system barrier) resulting from the corresponding piping failure. A core damage occurs mainly due to insufficient core cooling. An inspection will only reduce the failure frequencies. All terms will in general contribute to the risk of core damage. In many cases the dominating risk for high stressed welds will come from the rupture term in Eqn. (26) but for low stressed welds or thicker pipes the small leak term will be more important. In this study the system barrier C for core damage is set to 1.E-3 for a rupture or a large leak (> 30 kg/s) and 1.E-6 for a small leak (< 1 kg/s).

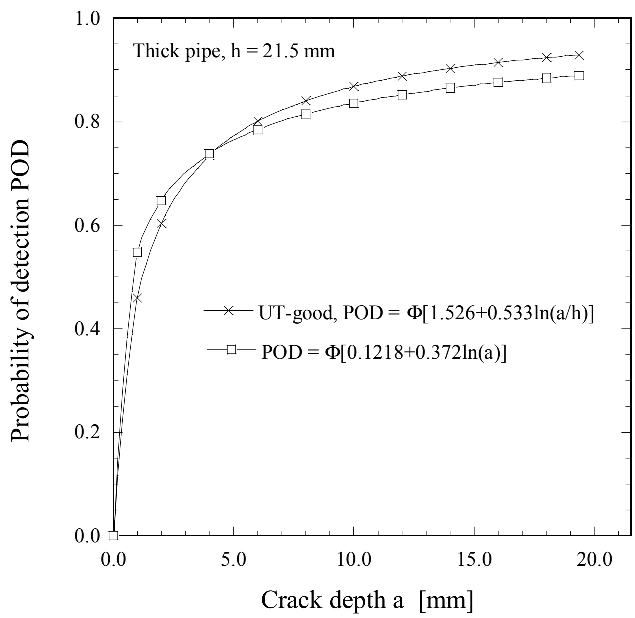

Fig. 14. Comparison of POD for a thick pipe.

The RRF is a measure of the effectiveness of the particular inspection method for reducing the risk for the component combined with the used inspection interval.

The result generated by NURBIT using POD from Eqn. (24) is shown in Fig. 15 in terms of risk reduction factor as function of the inspection interval.

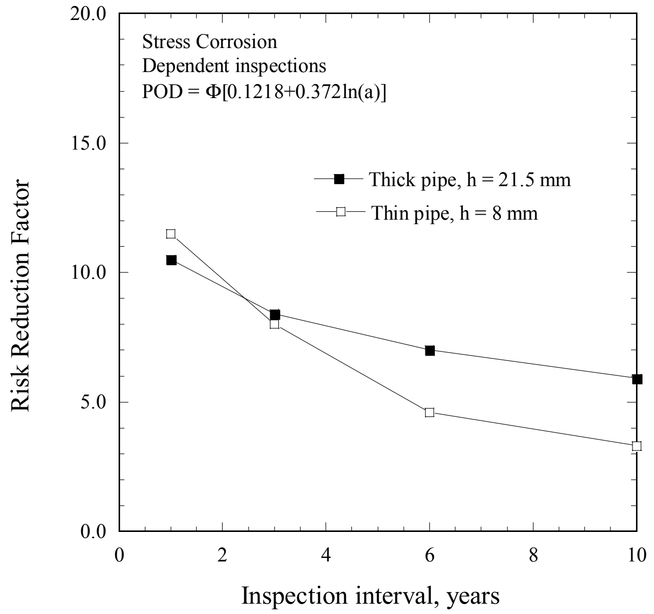

Fig. 15. Risk reduction factor as function of inspection interval for the thin and thick pipe and using dependent inspections.

An inspection interval of 1, 3, 6 and 10 years starting from year 2001 has been used in the evaluations. It is noted that a short inspection interval gives a larger risk reduction which is as expected. It should be noted that the absolute value of the CDF is larger for the thin pipe compared to the thick pipe. For the case of no inspections at all, CDF = 7.72E-9 per year for the thin pipe and CDF = 4.17E-10 per year for the thick pipe. This difference is due to lower leak- and rupture frequencies for the thick pipe which in turn is due to larger times to leak and rupture and larger leak flow rates (which is easier to detect) for the thick pipe. For use in risk-informed ISI, the relative difference of risk between these welds and the relative risk reduction due to inspections, are of most importance. Note also that in Fig. 15 dependent inspections are assumed. If two inspections are independent, the effect of performing two successive inspections would be larger than if the inspection was made only once, (p_{nd}^2 vs p_{nd}) where p_{nd} is the non-detection probability (1-POD). However, this can reflect an overestimation of the combined effect of the two inspections. If for some reason (e g due to a discontinuity in geometry), the crack was undetected during the first inspection, it is likely to be missed also during the next inspection. Therefore, as a conservative assumption, all inspections may be assumed to be dependent for which in a sequence of inspections, only the effect of the last inspection is considered. On the other hand, it may be argued that if the crack is missed at the first inspection due to a tight crack or a discontinuity in geometry at the weld location, then subsequent inspections will not do you any good anyhow. The problem is that it is almost impossible to have precise information of this kind (local geometry effects) for every location in order to correctly treat the benefit of a series of inspections. At this time, it can be regarded just as a conservative assumption if it is assumed that all inspections are completely dependent. The truth is probably lying somewhere between dependent or independent inspections.

Fig. 16 shows the similar result as Fig. 15 but now assuming independent inspections

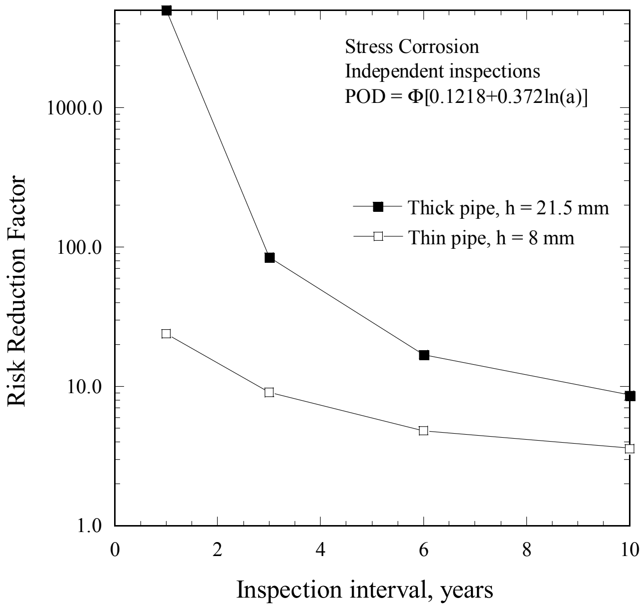

Fig. 16. Risk reduction factor as function of inspection interval for the thin and thick pipe and using independent inspections.

From Fig. 16 it is observed that independent inspections give a larger risk reduction, especially for the thick pipe with a small inspection interval. This is due to the fact that cracks in the thick pipe will have large times to leak (and rupture) and for a small inspection interval there will be time for many independent inspections before a leak is predicted and each of these inspections contribute to the overall risk reduction.

Fig. 17 shows the risk reduction factor for the thin pipe, comparing the POD defined in Eqn. (23) and (24) from the year 2001.

The better POD-performance of the "UT-good" POD-curve is reflected as a larger risk reduction, even if the difference is not very large for larger inspection intervals.

Finally, Fig. 18 shows the corresponding results for the thick pipe.

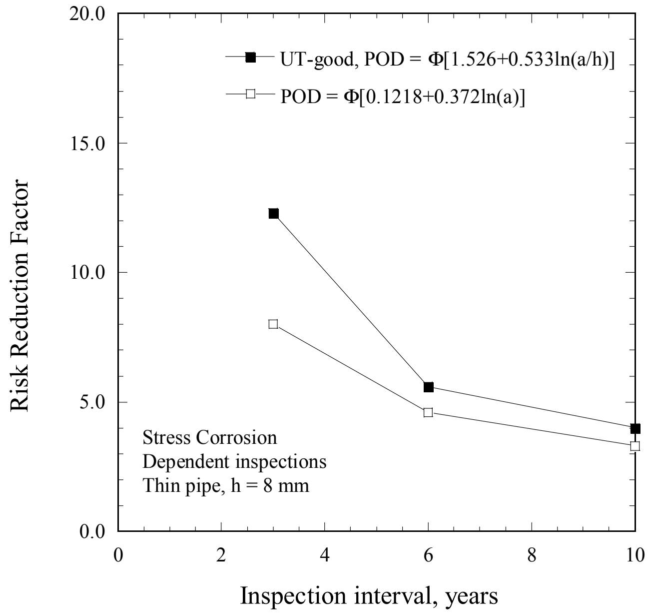

Fig. 17. Risk reduction factor for the thin pipe as function of inspection interval for different POD-assumptions. Dependent inspections are assumed.

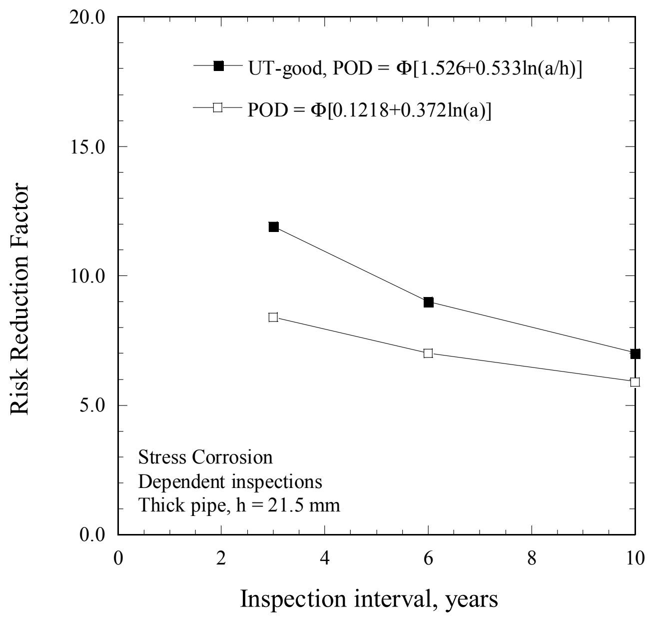

Fig. 18. Risk reduction factor for the thick pipe as function of inspection interval for different POD-assumptions. Dependent inspections are assumed.

Also in Fig. 18 a somewhat larger risk reduction is obtained using the “UT-good” POD-curve compared to the POD from Eqn. (24). A similar trend can be demonstrated if independent inspections are assumed.

5.2 Observations from section 5

1. The risk reduction from repeated inspections is a function of both the POD-curve and the inspection interval. To some extent, a less effective POD can be compensated for by using a shorter inspection interval.

2. A somewhat smaller risk reduction is obtained using the POD derived from the SQC database compared to the “UT-good” POD-curve from ref. /2/.

Note that this investigation has been done for the damage mechanism IGSCC, which gives a relatively rapid crack growth once cracks have been initiated. If one has a much slower crack growth mechanism, other observations can possibly be made even if the principal behaviour should remain the same.

6 Conclusions and recommendations

Based on the results in the previous sections, it can be concluded that

1. The POD is dependent on the absolute value of the crack depth (a). The POD will have the form $POD = \Phi[c_1 + c_2 \cdot \ln(a)]$, where Φ denotes the normalised Gaussian distribution.

2. Adding more variables to the model, for instance wall thickness, will not improve the model.

3. Fatigue cracks have a higher POD than IGSCC cracks even if the supporting data for IGSCC is sparse.

4. The POD is higher at qualifications tests than in the MTO-tests. Again, the supporting data for MTO is sparse.

5. A smaller risk reduction is obtained if the recommended POD is used in the RI-ISI analysis, instead of the POD by Simonen and Woo /2/.

It is recommended that the following POD for ultrasonic testing according to the Swedish UT-01 procedure should be used in a RI-ISI analysis,

UT-SQC $\quad POD = \Phi[0.1218 + 0.3720 \cdot \ln(a)]$

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/16/ SAS, Statistical Analysis System, version 8.2

Appendix A: Statistical Theory

A.1 GLIM, Generalized Linear Models

The statistical theory of *General linear models* (GLM), /9/, is used for regression analyses when data follow a Normal (Gaussian) distribution. The relationship between the response $\boldsymbol{y}$ (the variable of interest) and the explaining variables $\boldsymbol{x}$ is expressed as a linear function (in matrix terms): $\boldsymbol{y}=\boldsymbol{X\beta}+\boldsymbol{e}$, with independent normally distributed residuals $\boldsymbol{e}$, with constant variance. The mean value $\mathbf{E}(\boldsymbol{y})=\boldsymbol{X\beta}=\boldsymbol{\mu}$, is called the linear predictor. In reality other distributions are often the case, for example the Binomial distribution.

A more extended theory is *Generalized linear models* (GLIM), /10/, /11/, /12/, concerning the whole exponential family of distributions. A so-called link function is now explaining the mean linearly by the linear predictor: $g(\boldsymbol{\mu})=\boldsymbol{X\beta}$.

A1.1 The exponential family

The distribution of the variable *Y* belongs to the exponential family if the density can be written as

$$f(y)=\exp\left\{\frac{y\theta-b(\theta)}{a(\phi)}+c(y,\phi)\right\},$$

where

θ = canonical parameter, function of $\mu=\mathrm{E}(y)$,

ϕ = dispersion parameter,

a, b, c some functions *(a* is often the identity function*)*.

The parameters θ and ϕ are estimated with the maximum likelihood method (*i.e.* for a specific assumption of distribution they are defined in such a way that the probability for the observed result is maximized).

The Binomial, Gamma, Poisson or Normal distributions are examples of distributions belonging to the exponential family.

A1.2 Log likelihood function

For a distribution in the exponential family, the log likelihood function can be written

$$l=\ln(f(y,\theta,\phi))=\frac{y\theta-b(\theta)}{a(\phi)}+c(y,\phi).$$

The following relations are known from the likelihood theory.

$$\mathrm{E}\left(\frac{\partial l}{\partial \theta}\right) = 0 \text{ and } -\mathrm{E}\left(\frac{\partial^2 l}{\partial \theta^2}\right) = \mathrm{E}\left(\frac{\partial l}{\partial \theta}\right)^2,$$

which together with

$$\frac{\partial l}{\partial \theta} = \frac{y - b'(\theta)}{a(\phi)} \quad \text{and} \quad \frac{\partial^2 l}{\partial \theta^2} = -\frac{b''(\theta)}{a(\phi)},$$

from *l*, lead to the following expressions of mean and variance,

$$\mathrm{E}(Y) = b'(\theta),$$

$$\mathrm{Var}(Y) = a(\phi) \cdot b''(\theta).$$

As an example, the Binomial distribution, Y~Bin *(n, p)* with $\mathrm{E}(Y) = n \cdot p$, can be defined by the probability density

$$f(y, p) = \binom{n}{y} \cdot p^y \cdot (1-p)^{n-y} =$$
$$= \exp\left\{ y \cdot \ln\left(\frac{p}{1-p}\right) + n \cdot \ln(1-p) + \ln\binom{n}{y} \right\},$$

where

$$\theta = \ln \frac{p}{1-p}, \text{ and consequently}$$

$$p = \frac{\exp(\theta)}{1+\exp(\theta)} \text{ and } 1 - p = \frac{1}{1+\exp(\theta)}.$$

Further,

$$\phi = 1,$$
a = identy function,
$$b(\theta) = -n \cdot \ln\left(\frac{1}{1+\exp(\theta)}\right) = n \cdot \ln(1+\exp(\theta)).$$

and

$$c(y, \phi) = \ln\binom{n}{y},$$

which gives

$$f(y,p)=\exp\left\{y\cdot\theta-n\cdot\ln(1+\exp(\theta))+\ln\binom{n}{y}\right\}.$$

The mean and variance of the Binomial distribution are then given by

$$\mathrm{E}(Y)=b'(\theta)=n\cdot\frac{\exp(\theta)}{1+\exp(\theta)}=n\cdot p,$$

$$\mathrm{Var}(Y)=b''(\theta)=n\cdot\frac{\exp(\theta)\cdot[(1+\exp(\theta))-\exp(\theta)]}{(1+\exp(\theta))^2}=$$
$$=n\cdot\frac{\exp(\theta)}{(1+\exp(\theta))}\cdot\frac{1}{(1+\exp(\theta))}=n\cdot p\cdot(1-p).$$

A2. Link function

The link function g(***μ***)=***Xβ*** must be monotone and differentiable. The choice of link function depends on the type of data. Each distribution in the exponential family has a so-called canonical link, in the same form as the canonical parameter, $g(\mu)=\theta$. However, the canonical link is not necessarily always the best.

For the response *y/n*, where *Y*~Bin *(n,p)*, the mean is: $\mu=p$. Common for the Binomial distributions are the links:

probit: $g(p)=\Phi^{-1}(p)$,

logit: $g(p)=\log\left(\frac{p}{1-p}\right)$, (canonical link function)

CLL: $g(p)=\log(-\log(1-p))$. (Complementary Logit Link)

Their inverses, g^{-1}, restrict the mean to the interval [0,1]: $g^{-1}(g(p))=p\in[0,1]$. This is appropriate when the response, *i.e.* the estimated probability, only can take these values.

A2.1 Estimation of parameters

In what way the explaining variables $x_1, x_2, \ldots, x_{R-1}$ are affecting the response of the model is examined by estimating the parameters *β0 ,..., βR-1* with the log likelihood method. For a single observation, as before,

$$l=\ln(f(y,\theta,\phi))=\frac{y\cdot\theta-b(\theta)}{a(\phi)}+c(y,\phi).$$

The value for which the derivative of l with respect to the parameter β_j , equals zero maximizes l and gives $\hat{\beta}_j$, estimates for β_j , $j = 0,.. ,R-1$. Since θ is a function of μ, and $g(\mu) = X\beta = \eta$, the chain rule yields that the derivatives can be written

$$\frac{\partial l}{\partial \beta_j} = \frac{\partial l}{\partial \theta} \cdot \frac{\partial \theta}{\partial \mu} \cdot \frac{\partial \mu}{\partial \eta} \cdot \frac{\partial \eta}{\partial \beta_j} ,$$

where, $b'(\theta) = \mu$,

$$b''(\theta) = \frac{\partial \mu}{\partial \theta} = V \quad \text{(the variance function),}$$

$$\eta = X\beta = \sum_{j=0}^{R-1} x_j \beta_j \text{ with } \frac{\partial \eta}{\partial \beta_j} = x_j \text{ and}$$

$$W^{-1} = \left(\frac{\partial \eta}{\partial \mu} \right)^2 \cdot V .$$

This gives the expression

$$\frac{\partial l}{\partial \beta_j} = \frac{y - \mu}{a(\phi)} \cdot \frac{1}{V} \cdot \frac{\partial \mu}{\partial \eta} \cdot x_j = \frac{W}{a(\phi)} \cdot (y - \mu) \cdot \frac{\partial \eta}{\partial \mu} \cdot x_j .$$

By summing over all observations (i = 1, .. , N),

$$\frac{\partial l}{\partial \beta_j} = \sum_i W_i \cdot \frac{y_i - \mu_i}{a(\phi)} \cdot \frac{\partial \eta_i}{\partial \mu_i} \cdot x_{i,j} .$$

However, estimation of the parameters is usually done numerically.

Appendix B: Input Data for NURBIT

In this Appendix, the input data (except for the inspection parameters) is given to NURBIT, which is used in the evaluation of the risk reduction factors. Two pipe sizes are studied with a circumferential crack in the heat affected zone HAZ of a girth weld. One thin pipe with an outer diameter of 114.3 mm and wall thickness 8 mm and one thicker pipe with an outer diameter of 230 mm and wall thickness 21.5 mm.

B.1 THIN PIPE

B1.1 Geometry

Outside diameter 114.3 mm, wall thickness 8.0 mm. Initial crack depth 1 mm for initiated IGSCC. Mean value of initial crack length for circumferential IGSCC, $1/\lambda_0$ = 10.66% of inner circumference of pipe (exponential distribution).

B1.2 Stress conditions

Internal pressure 7.0 MPa at 285 °C which gives P_m = 19.9 MPa.

Dead weight primary bending stress P_b = 15 MPa.

Thermal expansion secondary bending stress P_e = 20 MPa.

Weld residual stress: Local through-wall thickness bending stress for a thin-walled pipe, equal to 218 MPa at the inside of the pipe and –218 MPa at the outside of the pipe. See Brickstad and Josefson /15/.

Upset load: Safety relief valve primary bending stress P_{SRV} = 30 MPa.

No vibration stresses are assumed.

B1.3 Material data (at 285 °C)

Stainless steel weld, type SMAW (Shilded Metal Arc Weld) and base material type 304 stainless steel SS are used.

Yield stress σ_Y = 150 MPa, Ultimate tensile stress σ_U = 450 MPa (Stainless Steel base material).

Fracture toughness J_c = 357 kN/m (SMAW Stainless Steel weld material at 2 mm stable crack growth).

IGSCC growth rate for cracks HAZ in stainless steels:

Normal Water Chemistry (NWC) $\frac{da}{dt} = 4.5 \cdot 10^{-12} K_{\mathrm{I}}^{3.0}$ mm/s

B1.4 Occurrence rate of IGCC

$f_{\mathrm{i}0} = 5.80 \cdot 10^{-4}$ per year, per weld side for a circumferential crack in the considered pipe system. This data is normally evaluated from individual damage statistics from the considered pipe systems for the particular plant.

B1.5 Leakage

Surface roughness 0.08 mm.

Pathway loss coefficient 0.282 mm^{-1}, corresponding to a large crack opening displacement just before rupture.

Discharge coefficient 0.95.

External pressure 0.1 MPa.

Detection limit for leak rate d = 0.3 kg/s, inside the containment.

B1.6 System barriers

For small leaks, the conditional core damage probability is here set to 1.0E-6. For a rupture it is set to 1.0E-3.

B1.7 Settings

Time at start of operation: 1975

Expected time at end of operation: 2015

Time of analysis equal to 2000.

1 year of operation is set equal to 8000 hours.

30 increments along the circumference for the integration of initial crack length.

B2 THICK PIPE

B2.1 Geometry

Outside diameter 230 mm, wall thickness 21.5 mm. Initial crack depth 1 mm for initiated IGSCC. Mean value of initial crack length for circumferential IGSCC, $1/\lambda_0$ = 10.66% of inner circumference of pipe (exponential distribution).

B2.2 Stress conditions

Internal pressure 7.0 MPa at 285 °C which gives P_m = 13.7 MPa.

Dead weight primary bending stress P_b = 15 MPa.

Thermal expansion secondary bending stress P_e = 20 MPa.

Weld residual stress: Local through-wall thickness bending stress equal to 85 MPa at the inside of the pipe and –85 MPa at the outside of the pipe. See Brickstad and Josefson /15/.

Upset load: Safety relief valve primary bending stress P_{SRV} = 30 MPa.

No vibrations are assumed.

The rest of the input data for the thick pipe are identical to the thin pipe.

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