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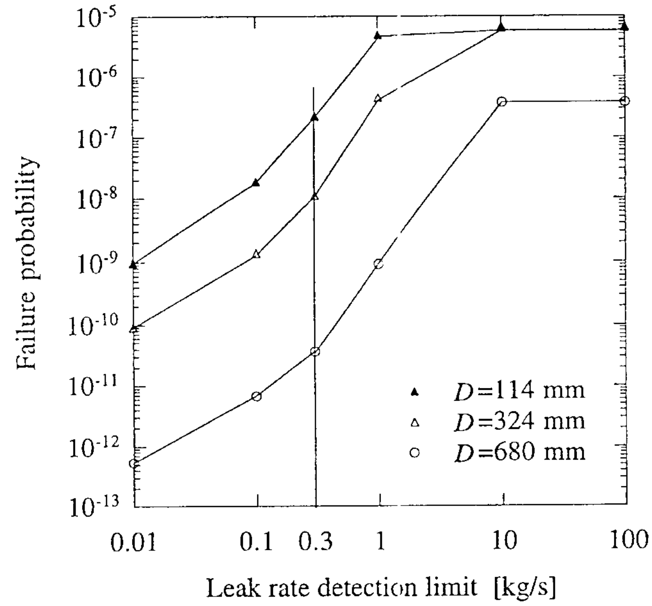

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ABSTRACT

A procedure has been developed for estimation of the failure probability of welds joints in nuclear piping susceptible to intergranular stress corrosion cracking. The procedure aims at a robust and rapid estimate of the failure probability for a specific weld with known stress state. Random properties are taken into account of the crack initiation rate, the initial crack length, the in-service inspection efficiency and the leak rate. A computer realization of the procedure has been developed for user friendly applications by design engineers. Some examples are considered to investigate the sensitivity of the failure probability to different input quantities.

NOTATION

D	Outer diameter of pipe
R_i	Inner radius of pipe
h	Wall thickness
d	Detection limit for leak rate
Δt	Inspection interval
T	Service life
t	Elapsed time since start up
a	Crack depth
a_0	Initial crack depth
l	Crack length
l_0	Initial crack length
$f_{al}(l_0)$	Probability density function for initial crack length
λ	Parameter of crack length distribution
λ_0	Value of λ for the reference set of data
$p_{nd}(a, l)$	Probability for non-detection at in-service inspection
c_1, c_2	Parameters of non-detection probability function

p_{ld}	Probability of non-detection of leak rate of size d
$f_{\mathrm{i}}(t_{\mathrm{i}})$	Probability density function for initiation time
f_{i0}	Crack initiation rate
t_{L}	Time to initial leakage
t_{F}	Time to fracture
$\dot{m}$	Leak rate
$\dot{m}(t_{\mathrm{F}})$	Leak rate just before fracture
μ_l	Mean value of leak rate
σ_l	Standard deviation of leak rate
μ_0	Conversion factor for leak rate
$p_{\mathrm{f00}}(l_0, t_{\mathrm{i}})$	Conditional fracture probability for given initial crack length and initiation time
$p_{\mathrm{f0}}(t, T, l_0)$	Conditional fracture probability for given initial crack length
p_{f}	Fracture probability for pipe section
K_{I}	Stress intensity factor
K_0	Parameter in crack growth law
ΔK_{th}	Threshold value for fatigue crack growth
J_{Ic}	Fracture toughness
σ_{Y}	Yield stress
σ_{U}	Ultimate tensile strength
σ_0, a_k	Parameters of residual stress distributions

INTRODUCTION

Probabilistic Safety Assessment (PSA) has become a standard tool for evaluating possible weaknesses in complex engineering structures such as nuclear power plant. In order to perform a probabilistic assessment of a system some assumptions about the failure probabilities of its components must be done. For many types of components observed failure frequencies are available and of such quality that they can be used in the assessment. For other types of equipment this is not the case. This is for instance not the case for nuclear piping which is the type of equipment under discussion in the present study. In past crude estimates about the probability of a pipe break in nuclear plants have been employed in PSA studies. Mostly the data from WASH-1400[1] or variations of this basic study have been used. The development in recent years of so called Probabilistic Fracture Mechanics (PFM) has shown that alternatives to the data of WASH-1400 may be obtained.

Both theoretical considerations and practical experience (*cf.* Bush[2]) indicate that Intergranular Stress Corrosion Cracking (IGSCC) is by far the most important process for pipe failure in Boiler Water Reactors. Very few failures, if any, of medium or large size piping have actually occurred, and this state of affairs precludes any estimation of the failure probability based on observed data. To estimate the failure probability analytical methods have to be used instead. The perhaps most well-known analytical vehicle for estimation of IGSCC failure probabilities is the PRAISE code described for instance by Harris *et al.*[3]. This program is however rather complicated and its structure is not readily transparent to the user. A simpler and perhaps more robust procedure was developed by Nilsson *et al.*[4]. In Ref. 4 a very simplified model was employed taking into account randomness in initial crack length, crack initiation rate, crack detection capability and loads. Although this model was not particularly detailed some interesting conclusions about the importance of different factors could be drawn. The model was however not so detailed that failure probabilities of individual pipe sections could be calculated. The treatment of the crack growth process was also done in a schematic fashion and no considerations of leakage detection were made. All in all this has prompted further refinement of the previous model. The general interest in obtaining better estimates of the pipe failure probabilities for use in plant specific PSA studies is another factor stimulating further development.

The objective of the present study has been to develop a procedure with accompanying computer software that can be used to estimate the fracture probability for a specific pipe section with prescribed local loading. The failure probability is strongly dependent on the actual loading conditions which makes it necessary to treat pipe systems on joint by joint basis. It is the intention of formulating the procedure and the software in such a way that operators of nuclear facilities can use it as an instrument in their continuing safety assessments. It therefore important to make the procedure simple and robust as well as easily adaptable to changes of input assumptions such as probability distributions.

MODEL ASSUMPTIONS AND THEORY

As mentioned above the present model is intended for calculation of the failure probability of a specific pipe cross section with a certain stress state and possibly containing a circumferential crack growing due to stress corrosion cracking. Since the term failure is used somewhat differently it is important to have a clear definition. With a failure is here meant that either $J \geq J_{Ic}$ or that the pipe suffers plastic collapse due to that the limit load is exceeded. J is here calculated by the R6-procedure and J_{Ic} is the corresponding fracture toughness. The following assumptions are made for the probabilistic analysis:

a) The stresses are assumed to be deterministic.

b) The crack growth law and its parameters are assumed to be deterministic

c) The initial crack depth is assumed to be fixed to 1.0 mm.

d) The probability that a crack with the assumed depth is initiated during the time interval $(t_i, t_i + dt)$ is given by $f_i(t_i)dt$.

e) The initial length of the crack is random with the probability density function $f_{al}(l_0)$.

f) The probability of not detecting a crack at an in-service inspection is $p_{nd}(a, l)$. In the present study the actual function used was not dependent on the crack length l, but a possible dependence on length is retained in the general equations.

g) The probability of not detecting a leak rate of a size corresponding to the detection limit d is p_{ld}.

Due to the assumptions made, the growth of the crack will be deterministic and will only depend on the initial crack length for a given geometry and given stresses. A procedure for calculating growth of such cracks has been developed by Bergman and Brickstad[5] resulting in a computer code named LBBPIPE. In Ref. 5 both surface cracks and through-the-thickness cracks were considered. The surface cracks in their work are characterised by the length along inner periphery l and the maximum depth a. The through-the-thickness cracks are characterised by the length along the inner and outer periphery, respectively. In both cases the shape of the cracks is given by parametric expressions so that reasonable shapes are obtained. By the computer program in Ref. 5 crack growth $(a(t), l(t))$ can be calculated to the time for penetration of the outer surface t_L and further to the time of fracture t_F. In addition the leak rate just before fracture $\dot{m}(t_F)$ can be calculated.

A certain surface crack of initial length l_0 and of initial depth a_0 in a pipe of diameter D and wall thickness h is considered. The initial depth is taken as common for all cracks and set to a small value (1.0 mm). The development of this crack can be calculated by the procedure in Ref. 5. In particular, the time of fracture $t_F(l_0)$ and the leak rate just before fracture $\dot{m}(t_F)$ can be obtained. Note that these two quantities are only functions of the initial crack length and that $\dot{m}(t_F) = 0$ for cracks that lead to fracture without penetrating the pipe wall.

Such a crack initiated at the time t_i is now considered. The following mutually excluding possibilities exist:

1) $t_i + t_F > T$, where T is the service life. Obviously this event gives no contribution to the fracture probability.

2) $t_i + t_F < T$ and $\dot{m}(t_F) > d$. Neither this event gives any contribution to the fracture probability.

3) $t_i + t_F < T$ and $\dot{m}(t_F) < d$ and the crack is detected by in-service inspections. This event gives no contribution to the fracture probability. The probability that the leak rate is not detected is handled through assuming a random behaviour of the leak rate so that

$$\mathrm{Prob}(\dot{m}(t_F) < d) = p_{ld}(l_0) . \tag{1}$$

4) $t_i + t_F < T$ and $\dot{m}(t_F) < d$ and the crack is *not* detected by in-service inspections. This event gives contribution to the fracture probability.

The probability for the alternative 4) to happen can easily be expressed as

$$p_{f00}(l_0, t_i) = p_{ld}(l_0) H(T-(t_i + t_F)) \prod_{j = j_1}^{j_2} p_{nd}(a(t_j - t_i), l(t_j - t_i)) , \tag{2}$$

where H is the Heaviside step function, t_j denotes the inspection times and

$$j_1 - 1 < \frac{t_i}{\Delta t} < j_1 , \tag{3}$$

$$j_2 < \frac{t_i + t_F}{\Delta t} < j_2 + 1 . \tag{4}$$

The relation (3) ensures that no inspection before the initiation time may be accounted for and likewise relation (4) ensures that no inspections after fracture may enter. Δt denotes the inspection interval which needs not to be constant. In eqn (2) the subsequent inspections are assumed to be statistically independent. To which extent this assumption is reasonable is presently unknown.

The expression (2) gives the conditional probability of fracture given the initial crack length and the crack initiation time. The random properties of the initiation time are taken into account by combining the probability density function for initiation time $f_i(t_i)$ with eqn (4) to obtain

$$p_{f0}(t, T, l_0) = \int_{\max(0,\, t - t_F)}^{T - t_F} p_{f00}(l_0, t_i) f_i(t_i) dt_i . \tag{5}$$

Here t is the time elapsed since start up for the period which the calculation is intended. The lower integration limit of the time integration in (5) accounts for the fact that a crack that has not led to fracture before the time instant t must have had an initiation time that is larger than $t - t_F$. In the calculation it is also assumed that $p_{nd}(a = h) = 0$, *i.e.* cracks leading to leakage will always be detected at an in-service inspection.

Finally the random distribution of the initial crack length has to be taken into account. This is done by integration of eqn (5) with respect to crack length with the probability density function for crack length as weight.

$$p_f(t,T) = \int_{l_c}^{2\pi R_i} p_{f0}(l_0, t_i) f_{al}(l_0) dl_0 . \quad (6)$$

The lower length limit l_c is the solution of the equation

$$t_F(l_c) = T . \quad (7)$$

REMARKS ON THE NUMERICAL PROCEDURE

In order to perform the probabilistic evaluations according to the procedure described a computer code named PIFRAP (PIpe FRActure Probabilities) has been developed (Bergman[13]) as an interface to the earlier described program LBBPIPE. PIFRAP calls upon LBBPIPE for different values of initial crack length and required quantities for the integration are obtained.

The version of LBBPIPE used here is somewhat modified in comparison with the previously released version (see Ref. 5). A database containing stress intensity factor and limit load solutions for circumferential surface cracks and through-the-thickness-cracks in a pipe has been extended to cover longer cracks than before. Up to complete circumferential surface cracks and through-the-thickness cracks with a length up to 80 percent of the inner periphery can now be analysed.

The integrations to provide the pipe break probability are performed using an extended trapezoidal rule. In case of evaluation of the normal Gaussian distribution function special care is taken to integration at the tails where a series expansion according to Abramowitz and Stegun[14] is used. All code has been written in Fortran 77 using double precision to minimise the risk of truncation errors.

ASSUMPTIONS ABOUT INPUT DATA

In order to check the procedure and also to obtain some information about the importance of different quantities a number of computer runs has been undertaken. For these runs a specific set of data referred to as the basic or reference case was defined. By varying the parameters sensitivity analyses have then been performed. It should be remarked that the structure of the model makes it very easy to change the assumptions about distributions and other data.

The probability density function for initial crack length was estimated from a total of 72 IGSCC-cases in Swedish stainless steel girth welds in straight pipes. In most cases the IGSCC was confirmed by metallographic evaluations. The frequencies of initial crack length relative to the inner circumference of each pipe are shown in Fig. 1. A correction was made for the observed crack lengths in order to obtain the initial crack lengths by subtracting an amount of crack growth at each crack-tip equal to the observed crack depth. This procedure was motivated by the observation that once the crack has been initiated the absolute crack growth in the depth and length direction is of the same order. A truncated exponential distribution, eqn (8), was fitted to this sample and is also shown in Fig. 1.

$$f_{al} = \frac{\lambda}{2\pi R_i}\exp\left(-\frac{\lambda l_0}{2\pi R_i}\right)(1-e^{-\lambda})^{-1}H(2\pi R_i - l_0) \quad (8)$$

The last two factors in eqn (8) are due to the truncation. The choice of an exponential distribution is not obvious but is motivated by its mathematical simplicity and that it is monotonously decreasing. The parameter λ was chosen with λ_0 equal to 8.26 so that the mean values of the observed and fitted distributions coincided. This corresponds to a mean value $1/\lambda_0$ of 12.1% of the inner pipe circumference and thus λ_0 was used as a reference value in the sensitivity analyses. If a subdivision is made with respect of pipe diameter the mean values according to Table 1 were obtained from 36 IGSCC-cases for each subdivision:

The cumulative number of IGSCC-cases in Sweden as function of number of service years is shown in Fig. 2. The sample represents 72 cases in Swedish BWR piping up to the year 1997. No elbow cracking is included in this sample, only welds. A more extensive account of all damage cases collected can be found in Appendix A. The straight line fit in Fig. 2 corresponds to an average occurrence rate of 2.9 cases per year. Estimating the total number of austenitic stainless steel girth welds in Swedish BWR-plants to be 20 000 then implies that f_i is constant and equal to $f_{i0} = 1.45 \cdot 10^{-4}$ per year per weld. This represents a total average such that if one would take an arbitrary weld from any one of the 20 000 welds, f_{i0} would represent the probability of that weld to contain a stress corrosion crack. Subdivisions are possible on individual pipe systems with respect to different dimensions, material and environmental conditions. This may cause f_{i0} to be both smaller and larger than the total average value. However, since the number of IGSCC-cases will be smaller for each subdivision the uncertainty in f_{i0} can be large for individual pipe systems. It should be realized that it is likely that for instance the stress state at a certain weld will influence the probability of initiation and thus that the dependence of the failure probability on stress is even larger than is found by the sensitivity study below. The PRAISE code (Ref. 3) contains a model for the initiation of stress corrosion cracks. It is, however, the opinion of the present authors that the current understanding of the initiation process is not so advanced that such a model is particularly meaningful.

The same relation for the non-detection probability at in-service inspections has been used as in the previous study (Ref. 4). This relation was given by Simonen and Woo[6] 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.

$$p_{nd} = 1 - \phi[c_1 + c_2\ln(a/h)]\,. \quad (9)$$

Here ϕ denotes the normalised Gaussian distribution function. c_1 and c_2 are constants taken from Ref. 6 and are shown in Table 2. The detection probability $(1 - p_{nd})$ is shown in Fig. 3. The term "poor" represents a lower bound performance among the teams that participated in programs to assess inspection efficiency (*cf.* Doctor *et al.*[7]). The term "good" represents a team with over average performance in the round robin trials that have been conducted and "advanced" represents a performance that may be achieved with further improved procedures. In the basic set of data the coefficients corresponding to "good" will be used. No dependence on the crack length l appears in eqn (9) and the authors have not been able to uncover any such information. In a study by Simola and Pulkkinen[8] no significant length dependence of the detection probability was found. This conclusion was not very firm, however, due to the limited amount of data.

The authors of the present article have not been able to find any results for the non-detection probability that are significantly different from those used here. In Ref. 8 the outcome from the PISC programme was analysed and the results were very similar to those of eqn (9). Simola and Pulkkinen[8] assumed a functional form of the non-detection probability functional of the same type as in ref. 7 and the coefficients obtained in their analysis are given for comparison in Table 2.

The leak rate in LBBPIPE is calculated using the computer code SQUIRT developed by Paul *et al.*[9]. The random properties of the leak rate are taken into account by aid of the results from Ghadiali and Wilkowski[10]. Their simulations indicate that the leak rate is normally distributed with a mean value μ_l given by the deterministic SQUIRT code and a standard deviation σ_l given by

$$\sigma_l = 0.4671199\mu_0\left(\frac{\mu_l}{\mu_0}\right)^{\left(0.8675548 - 0.0062139\ \ln\left(\frac{\mu_l}{\mu_0}\right)\right)}, \mu_0 = 0.063093 \text{ kg/s}. \tag{10}$$

This result was obtained by numerical simulations using the SQUIRT code with lognormally distributed morphology parameters. In the present simulations the normal distribution was truncated at zero flow in order to not obtain unrealistic results for small leak rates.

The basic set of input data consists of the data given above together with the specifications according to Tables 3-8. The information in the tables needs some explanatory remarks. Three pipe dimensions (small, medium and large diameter, respectively) according to Table 3 have been analysed.

The specifications for the weld residual stresses are taken from an investigation by Brickstad and Josefson[11]. The residual stress distribution is thus assumed in the following form.

$$\frac{\sigma}{\sigma_0} = \sum_{k=0}^{5} a_k\left(\frac{u}{h}\right)^k \tag{11}$$

Here u is a coordinate with origin at the inside of the pipe, σ_0 and a_k are constants given in Table 5. For the small and medium diameter piping this corresponds to pure local bending while for the large diameter pipe a more complicated distribution results.

The service loads are given in Table 4. The notation follows that of the ASME code. Besides the service loads (which contribute to the crack growth due to IGSCC), an additional load denoted complementary failure load can be analysed. This can be loads that may occur regularly such as thermal stresses during a turbine trip or loads with low probabilities such as water hammer or seismic loads. PIFRAP checks at every time instant if these additional loads will limit the time to leakage or failure. For every complementary failure load an occurrence probability is also assigned which will be included as a multiplicative factor in the failure probability. It is then not always the complementary failure load that is the most limiting load that controls the failure probability. In the examples shown below no complementary load case has been studied.

The material data used are shown in Table 6 and correspond to a stainless steel weld produced by Shielded Metal Arc Welding. The IGSCC growth data are given by a compilation by Bengtsson *et al.*[12] where the crack growth rate is assumed to follow eqn (12). Normal Water Chemistry (NWC) crack growth data is used for the reference cases and compared with Hydrogen Water Chemistry (HWC) in the sensitivity analysis.

$$\frac{da}{dt} = \begin{cases} \dot{a}_0\left(\frac{K_I}{K_0}\right)^3, & K_I \leq K_0 \\ \dot{a}_0 , & K_I > K_0 \end{cases} \quad , K_0 = 50 \text{ MPa}\sqrt{\text{m}}. \tag{12}$$

SENSITIVITY ANALYSES

The above described procedure as mentioned has been realized in the form of a computer code named PIFRAP. It is very convenient to perform sensitivity analyses by use of PIFRAP. This may give valuable information of the relative importance of different input data to the failure probability. One quantity at a time is varied while the others are fixed to their respective reference values.

In Fig. 4 the failure probability per year per weld is shown as function of the inspection interval for the three different pipe sizes. The vertical line represents the reference case, $\Delta t = 6$ years. These reference values are also shown in Table 9. There is a distinct effect of pipe diameter such that the larger the pipe diameter, the smaller failure probabilities are obtained. For a large diameter pipe, the crack will in general require longer times to propagate to leakage and to fracture. This means that there will be more time for inspections. Moreover, if $t_F - t_L > \Delta t$, there will always be at least one inspection for the leaking crack which is assumed always to be detected by ISI and this will give no contribution to the failure probability. Such events are more likely to occur for a large diameter pipe. That is why the difference in failure probability between different pipe diameters is more pronounced for short inspection intervals. Also, a large diameter pipe will in general have larger leak rates just before fracture which means that the probability of not detecting the crack by leak rate detection will be small. An inspection interval of 40 years means that no inspection at all is performed and it is observed that at least for the small and medium diameter pipe, an increase of the inspection interval from 6 years has only a marginal effect.

In Fig. 5 the failure probability for the medium size diameter pipe is shown as function of the inspection interval for the three different team performances as defined in Table 2. It is observed that the inspection interval has to be quite small in order to cause a significant reduction of the failure probability. The results for an inspection interval of 10 years differ very little from the results obtained when no inspections are performed at all.

The failure probability as function of the detection limit for leak rate is shown in Fig. 6. The reference value d = 0.3 kg/s is motivated by the technical specifications for the BWR-plants in Sweden which stipulate that the plant must be brought to a cold shut-down within one hour if an unidentified leak rate above 0.3 kg/s is discovered. A detection limit above 10 kg/s implies that virtually no leak rate is detected. This figure clearly demonstrates that leak detection is a very important factor for the failure probability. Depending on the pipe diameter, there will be a decrease of the failure probability between one and four orders of magnitude between the case of no leak detection and a detection limit of 0.3 kg/s. Typically $\dot{m}(t_F)$ is about 0.6 kg/s for the small diameter pipe and about 4 kg/s for the large diameter pipe. This means that a detection limit above 1 kg/s will have no effect on the failure probability for the small diameter pipe as shown in Fig. 6. The corresponding limit for the large diameter pipe is above 10 kg/s. If d is decreased to zero, all leak rates will be detected, no matter how small they are. This implies that the failure probability will tend to zero unless break occurs before leak.

The sensitivity of the failure probability to the initial crack length distribution is shown in Fig. 7. If $1/\lambda$ is increased, the value of the probability density function will be shifted to longer initial crack lengths. Long initial crack lengths will also give smaller t_F and $\dot{m}(t_F)$ which means that the failure probability will be an increasing function of $1/\lambda$. However, for the expected range of $1/\lambda$ between 9 and 15%, the relative change of the failure probability is rather modest.

The variation of crack growth rate for IGSCC is shown in Fig. 8. Different crack growth rates between the extreme cases Normal Water Chemistry (0% HWC) and Hydrogen Water Chemistry (100% HWC) were analysed. The difference between these conditions can be expressed by the level of conductivity and corrosion potential. In this respect 50% HWC means that during 50% of the time the environment at the crack is subjected to full HWC. It is observed that for the small and medium pipe diameter, 50% HWC will only result in a marginal decrease of the failure probability. On the other hand, if the crack growth rate is sufficiently small, the time to failure will be larger than 40 years for all initial crack lengths. This means that the failure probability will tend to zero in this model. For such piping systems, no stress corrosion crack will ever grow to failure within 40 years due to the slow crack growth rate. The limiting percentages of HWC for which this occurs are indicated with arrows in Fig. 8. This limiting value of percentage HWC is smaller for a large pipe compared to a small diameter pipe due to the fact that it takes a longer time to propagate a crack to failure in a large diameter pipe.

The failure probability as function of the level of weld residual stress is shown in Fig. 9. A weld residual stress ratio 1.0 corresponds to the reference case. A stress ratio of 1.5 means that the weld residual reference stress amplitude (σ_0) is multiplied by a factor of 1.5. It is observed that at least for the small and medium diameter pipe, the influence from the weld residual stress level is rather small. The explanation for this behaviour can be found in the way the residual stresses are distributed through the pipe thickness. The axial weld residual stresses are in general in force equilibrium over the wall thickness. Typically, a linear local bending stress is assumed for a thin-walled pipe. The axial weld residual stress is then more important for the surface crack growth than for the growth of the leaking crack. For a through-wall crack, a membrane stress or a global bending stress is more important contributors to the crack driving force and thus for the failure probability. This demonstrated in Fig. 10 where the sensitivity of the failure probability to the service load level (global bending stresses P_b and P_e) is shown. The reference case corresponds to mean values of P_b and P_e, based on a statistical evaluation of 316 welds reported in Ref. 4. In Fig. 10 the failure probability is also evaluated for the mean values of the loads plus and minus one standard deviation. The failure probability is very sensitive to the service load level. Both the crack growth rate and the limiting through-wall crack at failure are very much influenced by the bending loads. For the highest load level break occurs before leak for sufficiently long initial crack lengths. For these cases $t_F = t_L$ and thus p_{ld} will be 1.0. For the lowest load level, the time to failure exceeds 40 years for the large diameter pipe and hence the failure probability is zero for this case. This is indicated with an arrow in Fig. 10. It appeared that of all investigated parameters, the service load level had the largest relative influence on the failure probability.

The failure probability when the fracture toughness in terms of J_{Ic} is varied is shown in Fig. 11. The reference case $J_{Ic} = 385$ kN/m does not correspond to initiation but rather to a value of the J-resistance curve after a few mm of stable crack growth. The fracture toughness level controls the limiting crack size at failure and will influence primarily the amount of leak rate just before fracture. A high fracture toughness will result in a high $\dot{m}(t_F)$ and thus p_{ld} will be low. The influence of fracture toughness is larger for the large diameter pipe. This is due to the fact that a certain crack angle represents a much larger absolute crack length in a large compared to a small diameter pipe. This will cause a much larger J for the large diameter pipe and thus these pipes are more toughness sensitive than small diameter pipes. A small diameter pipe is more near limit load control and this is demonstrated in Fig. 12 where the sensitivity of the failure probability to the yield stress is shown. If the yield stress is increased from the reference value, the failure probability is significantly reduced for the small diameter pipe but is not changed much for the large diameter pipe. On the other hand, if the yield stress is decreased from the reference value the failure probability will increase for all pipe sizes. For a sufficiently low yield stress, yielding will occur at an early stage and this will also affect J through plasticity effects.

Finally, in Fig. 13 the influence of a vibration stress amplitude is shown. The procedure in PIFRAP accounts for vibration fatigue in combination with IGSCC in a simplistic way. If a non-zero vibration stress is specified, a check is made at every time instant if the range of stress intensity factor exceeds the threshold value ΔK_{th}. If this is the case, then leakage and fracture is assumed to occur instantly (unless K_I is less than ΔK_{th} for the recharacterized through-wall crack). The basis for this procedure is given in Ref. 5 where it is shown that if the threshold value is exceeded, high cycle fatigue will give a very rapid crack growth with only a few hours difference between leakage and fracture. This is a simplified treatment which relies on the assumption that vibrations will occur with a high and constant frequency and with a constant stress amplitude. In reality many different frequencies as well as many different stress amplitudes are involved in a vibration stress history. For high vibration stress amplitudes in Fig. 13, ΔK_{th} is exceeded already for the surface crack and failure is predicted without any prior leakage. This means a break before leak situation and no credit can be taken from leak detection ($p_{ld}=1.0$) which will give high failure probabilities. In all cases ΔK_{th} is assumed to be 4.0 $\mathrm{MPa}\sqrt{\mathrm{m}}$. For lower vibration stress amplitudes in Fig. 13, the surface crack will grow to a stable leak due to IGSCC and ΔK_{th} is not exceeded until some amount of growth of the leaking crack.

It can be of some interest to rank the different input parameters in terms of their relative importance for the failure probability. Averaging for all pipe diameters, the following ranking list has been obtained:

a) Service load level P_m, P_b and P_e.

b) Yield stress.

c) Vibration stress amplitude.

d) Detection limit for leak rate.

e) Inspection interval.

f) Crack growth rate data (percentage HWC).

g) Fracture toughness.

h) Weld residual stresses.

i) Mean value of initial crack length distribution.

CONCLUSIONS

The procedure outlined represents an efficient and robust tool to estimate the failure probability due to IGSCC in nuclear piping systems. It is believed that the main contributors to the failure probability are accounted for by the model. Sensitivity studies can be performed very conveniently. The greatest source of error is the input data. An observation from this study is that there is a distinct effect of pipe diameter such that the larger the pipe diameter, the smaller failure probability results. Also, leak detection is a very important factor in order to maintain a low failure probability. For the reference cases with $d = 0.3$ kg/s, it corresponds to performing inspections with an interval of approximately 3 years.

A procedure of the present type appears to be a valuable tool for allocating resources for In-Service Inspection ISI. A recommendation from this study would then be to devote efforts for ISI to austenitic stainless steel welds in small and medium size piping with normal water chemistry and where the service load level is high. In the general case of a risk based inspection procedure this has to be complemented with an analysis of consequences of a pipe break at different locations.

Possible refinements of the procedure in this paper could be a more elaborate model for crack initiation. Also the model for not detecting a through-wall crack with leak rate detection could possibly be refined.

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FIGURE CAPTIONS

Fig. 1 Observed lengths for IGSCC cracks that have been measured in Swedish BWRs together with assumed probability density function for initial crack length.

Fig. 2. Accumulated number of IGSCC-cases in Swedish BWR piping.

Fig. 3 The probability of detection.

Fig. 4. The failure probability as function of inspection interval.

Fig. 5. The failure probability as function of inspection interval and NDT-performance for the medium pipe diameter.

Fig. 6. The failure probability as function of detection limit for leak rate.

Fig. 7. The failure probability as function of $1/\lambda$ in the initial crack length distribution.

Fig. 8. The failure probability as function of crack growth rate data in terms of percentage of Hydrogen Water Chemistry.

Fig. 9. The failure probability as function of the level of weld residual stress.

Fig. 10. The failure probability as function of the service load level.

Fig. 11. The failure probability as function of fracture toughness J_{Ic}.

Fig. 12. The failure probability as function of yield stress.

Fig. 13. The failure probability as function of vibration stress amplitude.

TABLE CAPTIONS

Table 1. Parameter of initial size distribution

Table 2. Coefficients of non-detection function

Table 3 Geometry parameters of reference cases

Table 4 Service loads for reference cases

Table 5 Residual stress distribution for reference cases

Table 6 Material properties

Table 7 Parameters for leak rate calculation

Table 8 Inspection parameters

Table 9 Failure probability per year and per weld for the basic set of data and respective pipe size.

D/mm	$1/\lambda_0$
< 200	9.73%
≥ 200	14.5%

Table 1

Type of inspection team	c_1	c_2
poor	0.240	1.485
good	1.526	0.533
advanced	3.630	1.106
From ref. 8	1.64	0.75

Table 2

Case	D/mm	h/mm
small diameter pipe	114	10
medium diameter pipe	324	17.5
large diameter pipe	680	40

Table 3

Case	Internal pressure/MPa	P_m /MPa	P_b /MPa	P_e /MPa
small diameter pipe	7.0	18	16.6	48.9
medium diameter pipe	7.0	31	16.6	48.9
large diameter pipe	7.0	28	16.6	48.9

Table 4

Case	σ_0 /MPa	a_0	a_1	a_2	a_3	a_4	a_5
small diameter pipe	198	1.0	-2.0	0	0	0	0
medium diameter pipe	124	1.0	-2.0	0	0	0	0
large diameter pipe	79.4	1.0	3.8116	-99.82	339.97	-404.59	158.16

Table 5

Yield stress σ_Y /MPa	Tensile strength σ_U /MPa	Fracture toughness J_{Ic} /kNm^{-1}	$\dot{a}_0$ /mms^{-1} N W C	$\dot{a}_0$ /mms^{-1} H W C	$\Delta K_{th}/(\text{MPa}\sqrt{\text{m}})$
150	450	385	$5.6 \cdot 10^{-7}$	$2.5 \cdot 10^{-8}$	4.0

Table 6

Surface roughness/mm	Pathway loss coefficient $/mm^{-1}$	Discharge coefficient	External pressure/MPa	d/kgs^{-1}
0.08	28.2	0.95	0.1	0.3

Table 7

Δt /years	T/years	t/years	Number of hours per year of operation
6	40	20	8000

Table 8

Case	p_f per year
small diameter pipe	$2 \cdot 10^{-7}$
medium diameter pipe	$1 \cdot 10^{-8}$
large diameter pipe	$4 \cdot 10^{-11}$

Table 9

Fig. 1

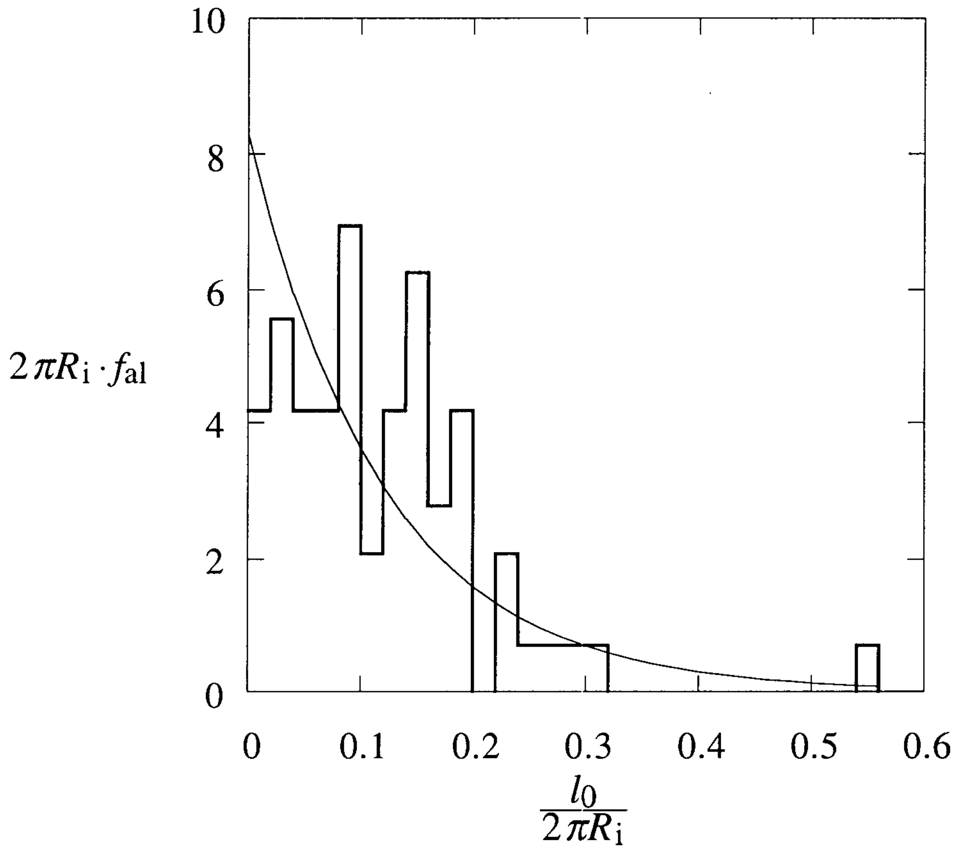
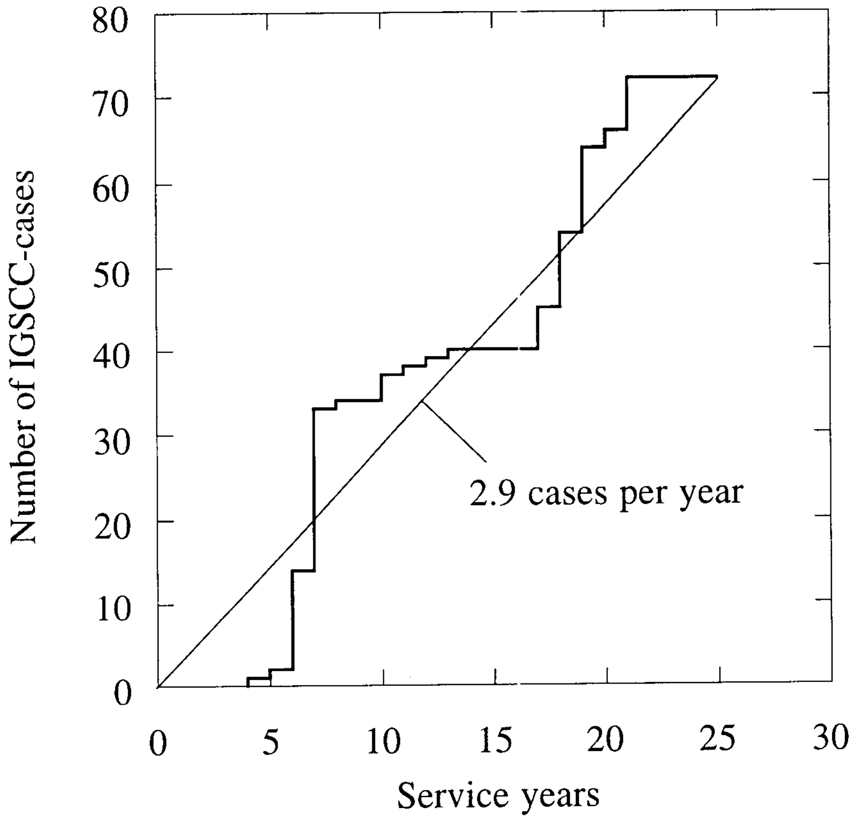
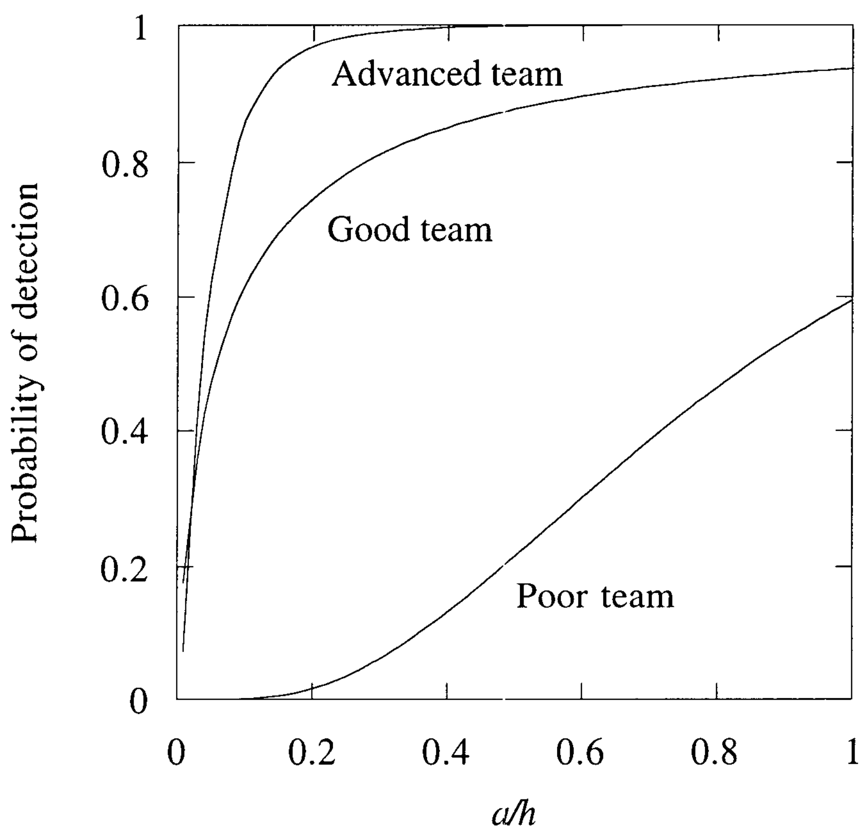


Fig. 2



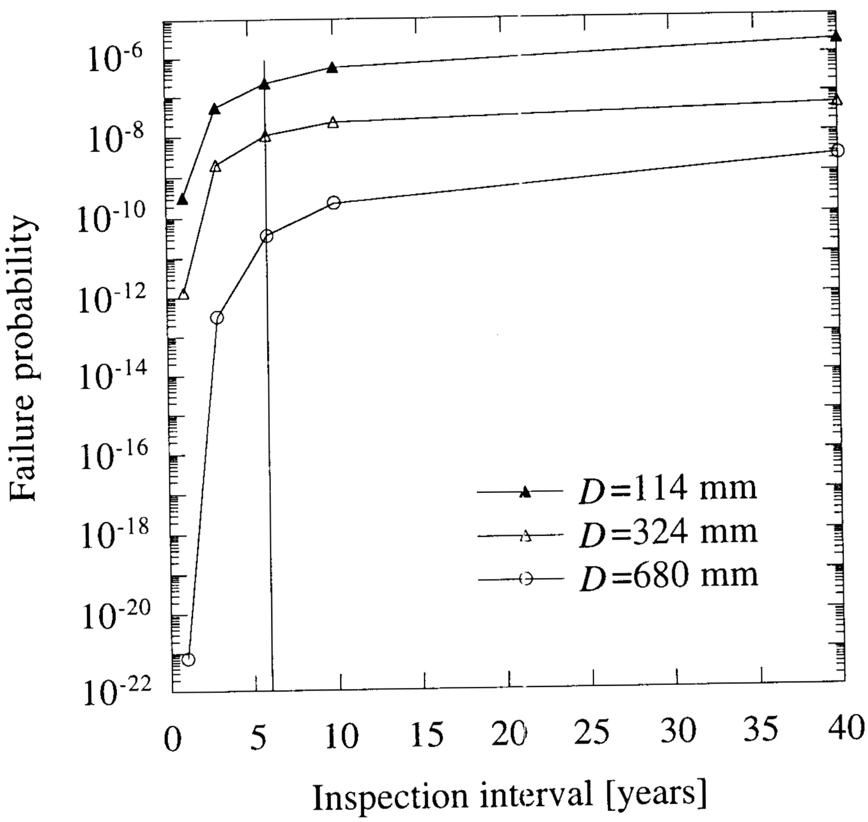
80
70
60
50
40
30
20
10
0
Number of IGSCC-cases
2.9 cases per year
0
5
10
15
20
25
30
Service years

Fig. 3



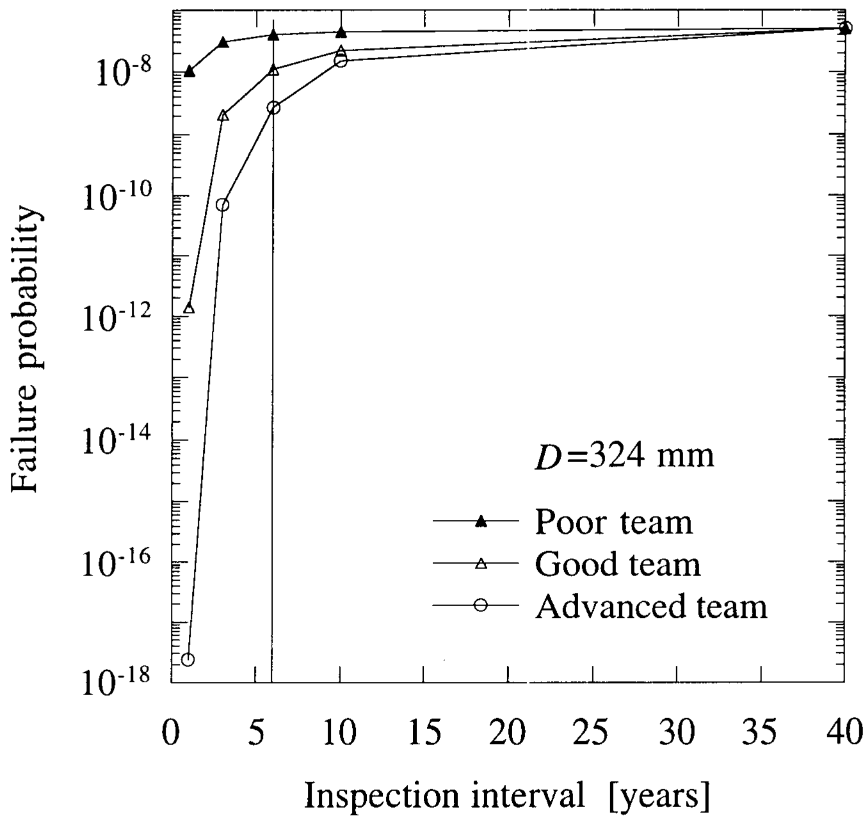
Advanced team
Good team
Poor team
Probability of detection
0
0.2
0.4
0.6
0.8
1
a/h

Fig. 4



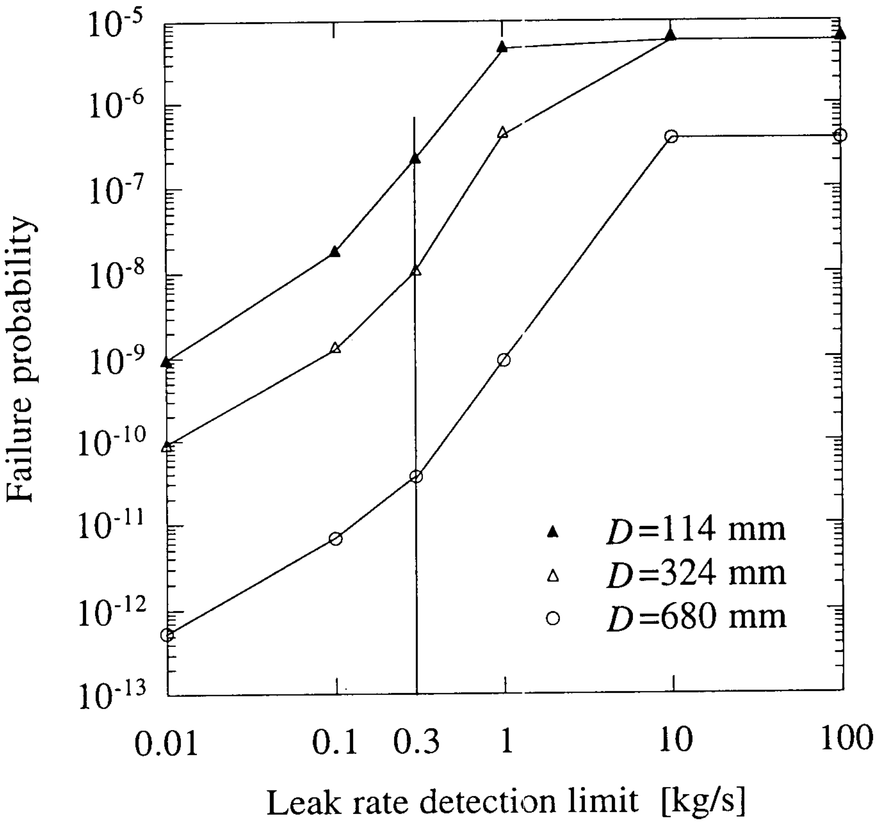
Failure probability
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
0 5 10 15 20 25 30 35 40
Inspection interval [years]
D=114 mm
D=324 mm
D=680 mm

Fig. 5



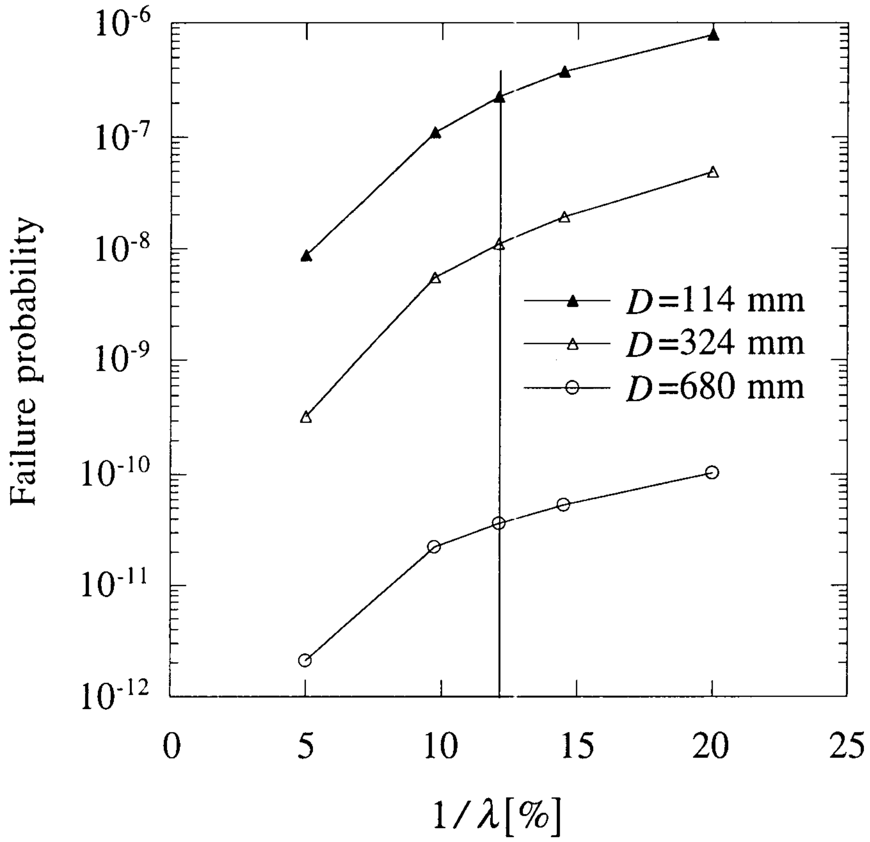
Failure probability
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
0
5
10
15
20
25
30
35
40
Inspection interval [years]
D=324 mm
Poor team
Good team
Advanced team

Fig. 6



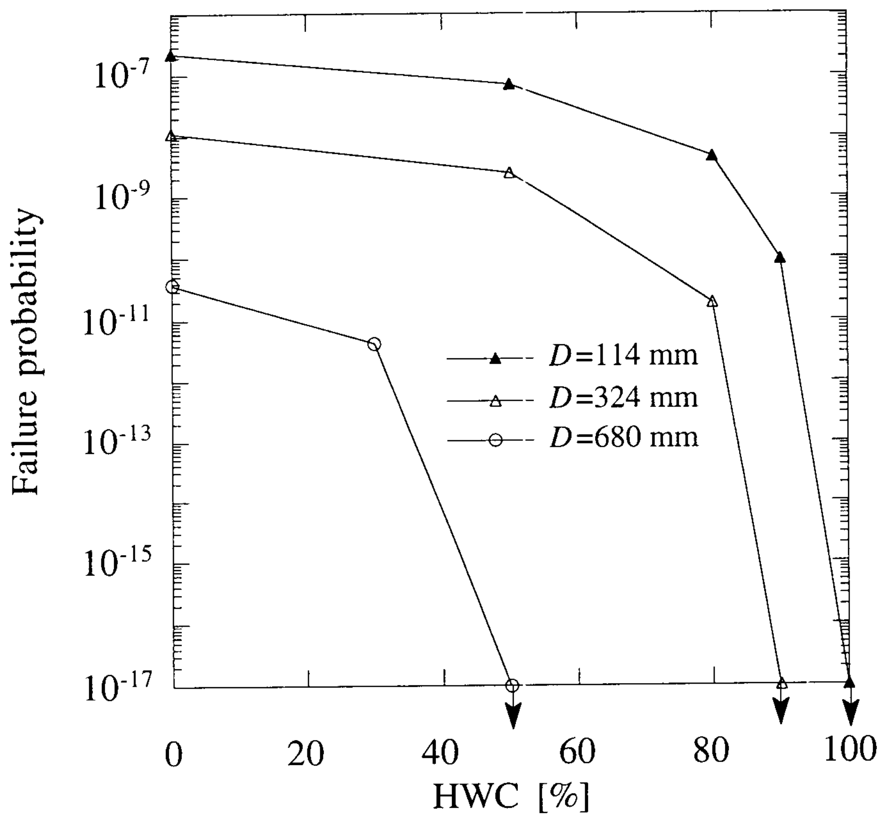
Failure probability
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
10-13
D=114 mm
D=324 mm
D=680 mm
0.01
0.1
0.3
1
10
100
Leak rate detection limit [kg/s]

Fig. 7



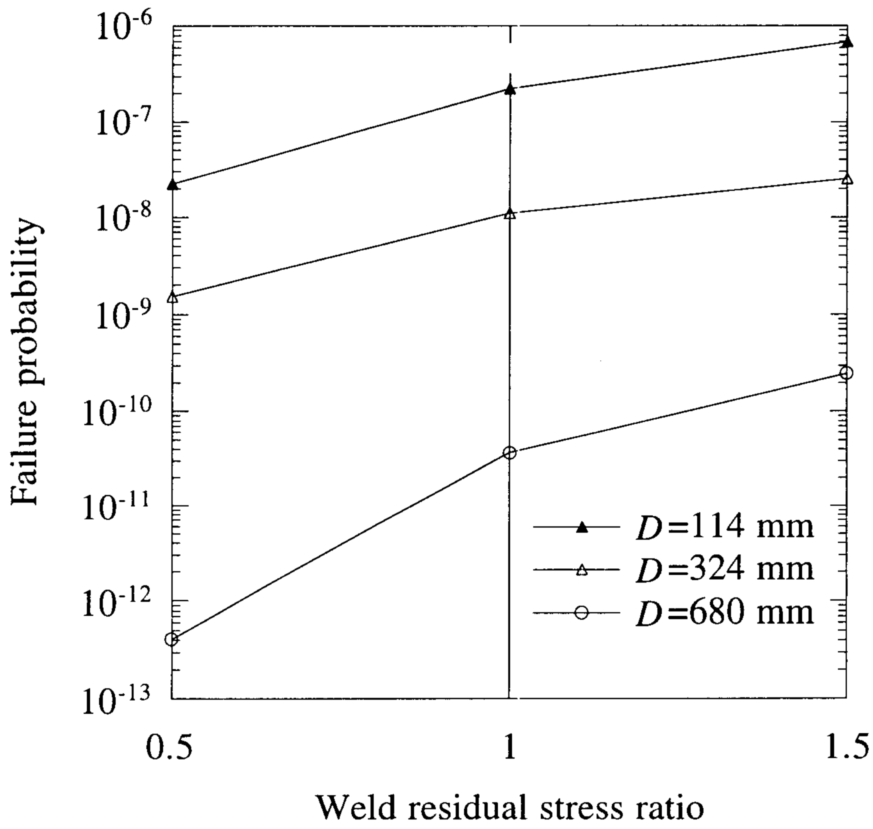
10-6
10-7
10-8
10-9
10-10
10-11
10-12
Failure probability
D=114 mm
D=324 mm
D=680 mm
0
5
10
15
20
25
1/λ[%]

Fig. 8



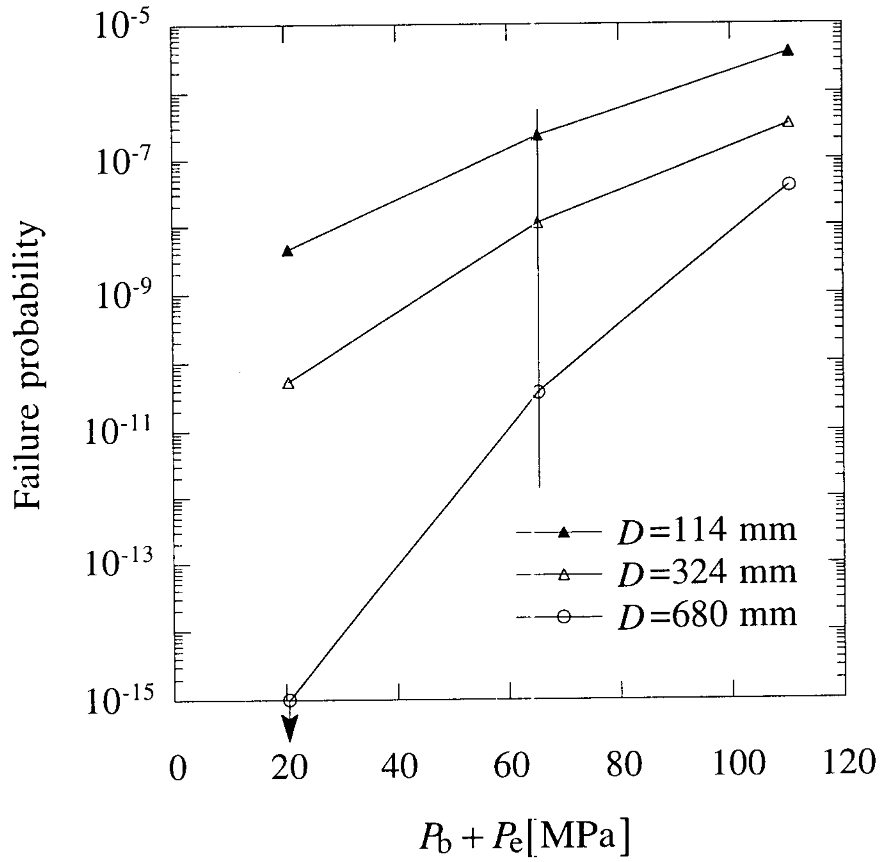
Failure probability
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
0
20
40
60
80
100
HWC [%]
D=114 mm
D=324 mm
D=680 mm

Fig. 9



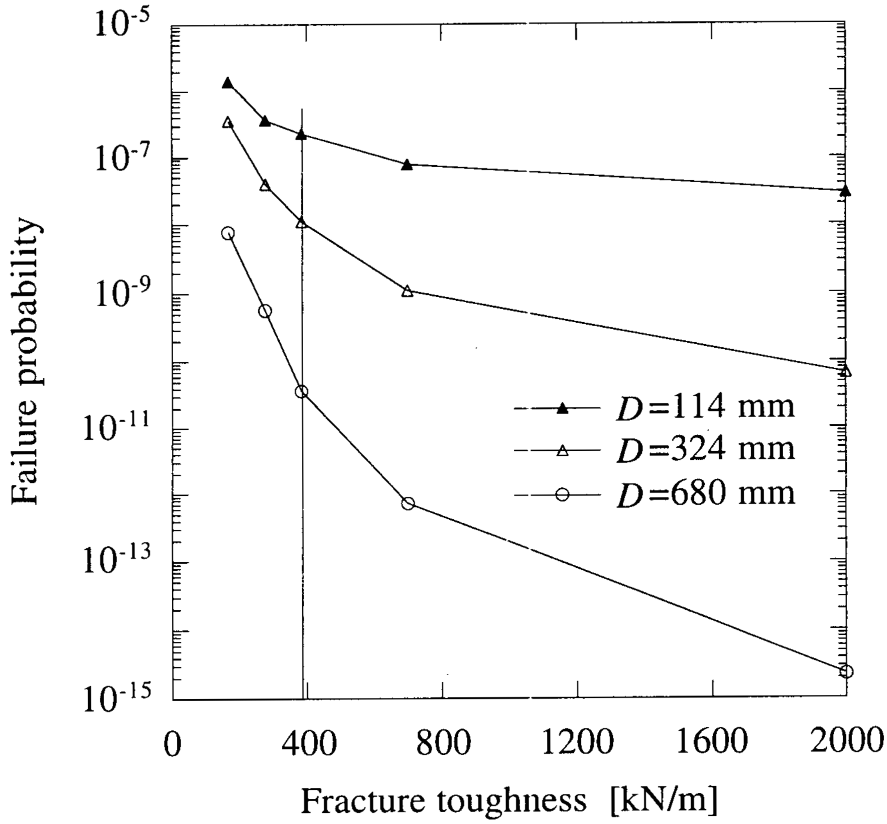
Failure probability
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
0.5
1
1.5
Weld residual stress ratio
D=114 mm
D=324 mm
D=680 mm

Fig. 10



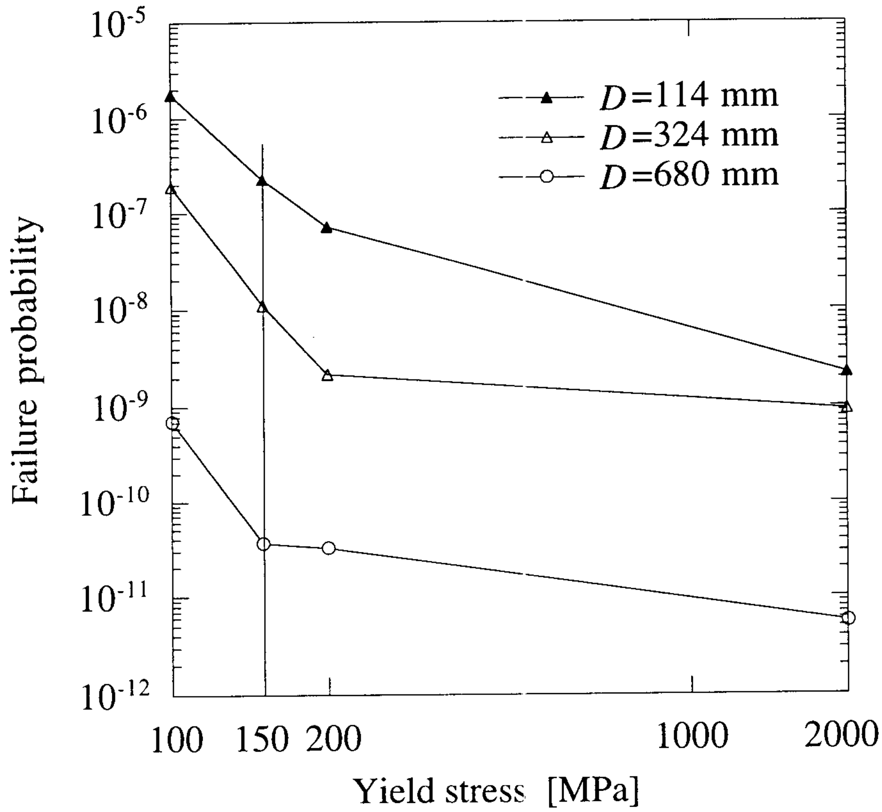
10-5
10-7
10-9
10-11
10-13
10-15
Failure probability
D=114 mm
D=324 mm
D=680 mm
0
20
40
60
80
100
120
Pb + Pe[MPa]

Fig. 11



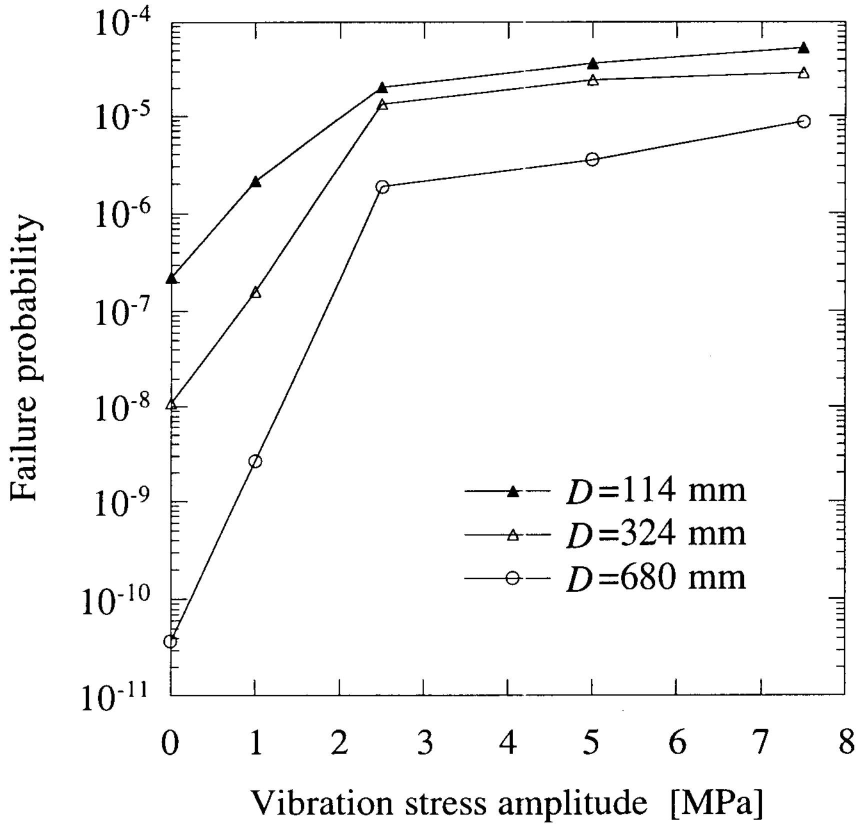
10^-5
10^-7
10^-9
10^-11
10^-13
10^-15
Failure probability
0
400
800
1200
1600
2000
Fracture toughness [kN/m]
D=114 mm
D=324 mm
D=680 mm

Fig. 12



Failure probability
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
D=114 mm
D=324 mm
D=680 mm
100
150
200
1000
2000
Yield stress [MPa]

Fig. 13



Failure probability
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
0
1
2
3
4
5
6
7
8
Vibration stress amplitude [MPa]
D=114 mm
D=324 mm
D=680 mm

F2-321-87	273 x 21	2	220	.303	.2976	A1
F1-321-87	273 x 21	5.1	45	.062	.0480	A1, A3
F2-331-87	168 x 14.8	4.5	65	.149	.1288	A1
F1-321-87	273 x 21	6.8	35	.0482	.0295	A1, A3
F1-321-87	273 x 21	3.4	20	.0276	.0182	A3
O2-331-91	168.3 x 12.5	6.5	55	.122	.0933	A1
O2-331-91	168.3 x 12.5	2.5	75	.167	.1555	A1
O2-331-91	168.3 x 12.5	2.5	90	.200	.1888	A1
O2-331-91	168.3 x 12.5	2.5	30	.0666	.0555	A1
O2-331-91	139.7 x 11	2.5	70	.189	.1758	A1, A3
O1-326-91	168.3 x 12.5	7	80	.178	.1466	A1, A3
F2-321-91	323 x 17.5	3.7	150	.166	.1576	A1
F2-321-91	323 x 17.5	1	25	.0276	.0254	A1
F2-321-91	323 x 17.5	2	90	.0995	.0951	A1
F1-321-94	273 x 21	4	233	.321	.3100	A3
B2-326-95	168.5 x 13	11	110	.246	.1966	A3, A5
B2-321-95	210 x 12.5	5	150	.258	.2409	A3, A5
B2-321-95	210 x 12.5	6	150	.258	.2374	A3, A5
B2-321-95	210 x 12.5	5	110	.189	.1721	A3, A5
B2-321-95	210 x 12.5	7	70	.120	.0964	A3, A5
B2-321-95	210 x 12.5	4	122	.210	.1961	A3, A5
B1-313-95	114 x 8	4	60	.195	.1689	A4
B1-321-96	218 x 18	15	100	.175	.1224	A6
B1-321-96	210 x 14	6	150	.262	.2414	A6
B1-321-96	218 x 17	6	95	.164	.1436	A6
B1-321-96	218 x 17	5	55	.0951	.0778	A6
B1-321-96	218 x 17	7	330	.571	.5466	A6
B1-321-96	218 x 18	7	71	.124	.0997	A6
B2-321-96	230 x 18	3	85	.139	.1296	A7
B2-321-96	230 x 18	4	95	.156	.1427	A7
B2-321-96	230 x 15	9.5	90	.1432	.1130	A7
B2-354-96	76 x 7	5	26	.133	.0821	A7
B2-321-96	269 x 21	9.1	135	.171	.1482	A7
B2-321-96	269 x 21	-	65	.0825	.0698	A7
B2-321-96	269 x 21	9.3	205	.26	.2366	A7
B2-321-96	267 x 22	8	80	.114	.0914	A7

B2-321-95	267 x 19	6	100	.1390	.1223	A5
B2-313-97	217 x 16	5	100	.1721	.1549	A8
B2-321-96	266 x 17	6	215	.2950	.2798	A7
B2-321-95	210 x 15	4	120	.2122	.1981	A5
B2-321-95	267 x 22	6	100	.1427	.1256	A5

Notation

a Crack depth

l Crack length

l_0 Initial crack length

D Outer diameter of pipe

R_i Inner radius of pipe

h Wall thickness

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