Key Engineering Materials
ISSN: 1662-9795, Vol. 820, pp 60-74
doi:10.4028/www.scientific.net/KEM.820.60

Submitted: 2018-09-15
Revised: 2019-04-25
Accepted: 2019-04-29
Online: 2019-09-04

Effect of Corrosive Environment Conditions on Austenitic Structure Reliability

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Keywords: Reliability; Fracture mechanics; Corrosion cracking.

Abstract. In this paper, the work is based on the application of probabilistic fracture mechanics models (PFM) to predict the reliability of nuclear reactors pipes under pressure. Cracking simulation of a stainless steel piping under the conditions of intergranular stress corrosion cracking (IG-SCC) is based on the general methodology recommended in the modified software M-PRAISE. IG-SCC is characterized by a unique damage parameter depending on residual stresses, environmental conditions, and sensitization degree. This parameter can be used to evaluate the structural reliability and identify the majority of efficient approaches to improve the piping reliability: effect of a corrosive medium on the reliability, which is analyzed in this present work.

Introduction

Damage detection and quantification meaning (knowing when it initiates, knowing where it initiates, determining its propagation mode(s) and determining its interactions with the microstructure). Leads us to the understanding, modelisation and prediction of environmentally assisted cracking processes (Stress Corrosion, Fatigue-Corrosion, and Hydrogen Embrittling). It is, therefore, possible to evaluate the respective role of the different chemical, mechanical, and metallurgical intervening parameters, necessary steps to establish phenomenological models and to quantify the effect of these parameters in order to take them into account in a micromechanical modelisation. Stress corrosion cracking (SCC) is one of the important mechanisms in the degradation of steels. This mechanism induces material cracking due to a combined action of a sensitive material, a tensile stress, and corrosive environment (see Fig. 1). In the piping of a boiling water reactor, the sensitive material near welds is the stainless steel.

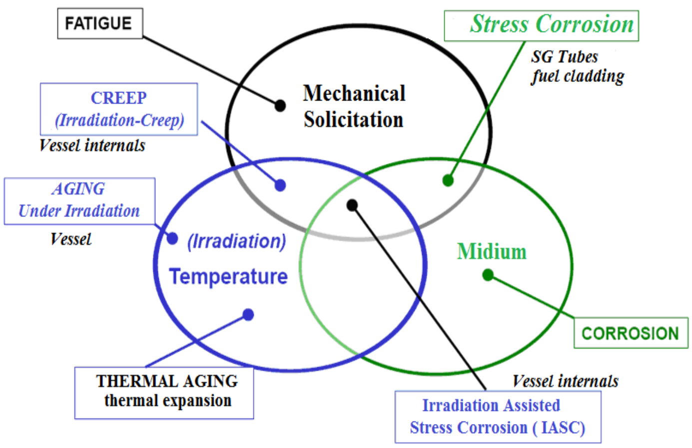

Fig.1: Main types of aging and damage.

The sensitivity of this material to cracking by SCC is due to the precipitation of chromium carbide at the grain joints learning immediately adjacent areas of the grain joints with a lower chromium grade [1]. Zhang and al. [2] have done experimental verification to determine the initiation time and the propagation rate of IGSCC in sensitised stainless steel in diluted sulfate solutions. Many researchers [3-10] have approached the probabilistic analysis of components failure due to SCC based on fracture mechanics. Piping component failure probabilities under SCC, including the effects of residual stresses, have been realized by Guedri and al. [11-12] using Monte Carlo simulation technic's (MCS). The results of these studies have been used to develop the input data for the analysis of failure probabilities. This paper is structured as follows: The first part on reliability generalities, the second part is a general description of the piping reliability model, and the third part presents an application example and analysis of the results of this study. Finally, a general conclusion regrouping the analysis methodology and the obtained results.

Reliability Evaluation

Recommended methodology. PRAISE Code has been widely documented, successfully applied to structural integrity problems, and is available since the 80's. However, the code has not been maintained or improved in a constant manner. Code Updating has been done to satisfy the actual application requirements and to fill in the gaps concerning the very specific PRAISE capabilities. The recommended methodology in the modified PRAISE version (M-PRAISE) [13, 14], the modelisation of SCC in piping will be presented succinctly. In M-PRAISE, the occurrence of SCC modelised by considering it as a two-step process, such as first crack initiation followed, in a second step, by a crack propagation (see Fig. 2). The aim of this work has been to evaluate the effects of the environment changes in terms of failure probabilities; the improved modified PRAISE version (M-PRAISE) [13, 14] takes into account the initiation in multiple sites by dividing the piping circumference.

Initiation and propagation of cracks due to SCC.

Time to initiation. The time to SCC initiation is considered as a function of the damage parameter D, which represents the effects of loading, environment and material on SCC (see Fig. 3).

The damage parameter is given by [12]:

$$D = f_1 \text{ (material) x } f_2 \text{ (environment) x } f_3 \text{ (loading)}. \tag{1}$$

where f_1, f_2 and f_3 are given by:

$$f_1 = C_1 \left(Pa\right)^{C_2}. \tag{2}$$

where Pa is a measure of the sensitization degree, given by EPR (Electrochemical Potentiokinetic Reactivation) in (C/cm^2).

$$f_2 = O_2^{C_3} \exp\left[C_4 / \left(T + 273\right)\right] \log\left(C_5 \, \gamma^{C_6}\right). \tag{3}$$

where O_2 is the oxygen concentration (ppm), T the temperature in centigrade degrees, and γ is the water conductivity in (µs/cm).

The loading term f_3 is considered as a function of stress. In the case when a constant load is applied, f_3 is given by:

$$f_3 = \left(C_8 \, \sigma^{C_9}\right)^{C_7}. \tag{4}$$

where σ is the stress (ksi) (1 ksi = 6.895 MPa) C_1 to C_9 are constants whose values depend on the type of material, and evaluated through a nonlinear regression from the laboratory data.

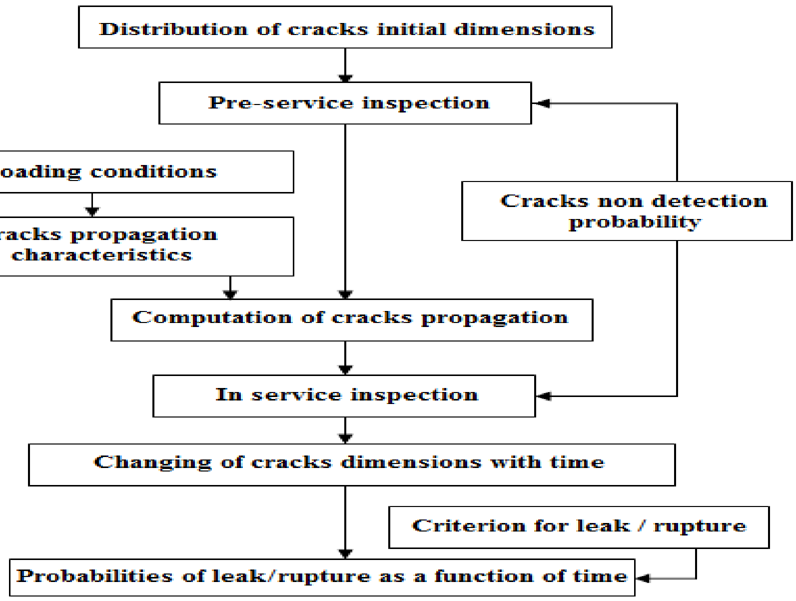

Fig. 2: Computation of the probability of failure.

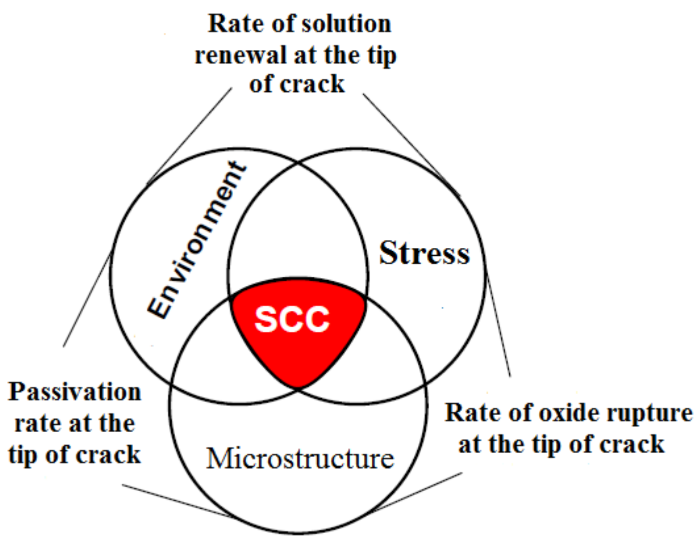

Fig. 3: Sensitivity space to stress corrosion cracking.

For the austenitic stainless steel AISI 316 NG, the values of these constants are given in Table 1.

Table 1: Constant's values for austenitic stainless steel AISI 316 NG [12].

Constant	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Value	1.879	0.00	0.24	-1123.0	4.0	0.35	0.49	2.21E-15	6.00

In order to satisfy the initiation time dispersion observed in the experimental data, the initiation time (t_i) for a given damage (D) is considered as a random variable following a log-normal distribution. The mean value and the standard deviation of the log (t_i) are given equation Eq. (5):

$$\left.\begin{array}{l}\text{The Mean value of } \log(t_i) = B_0 + B_1\log(D), \\ \text{The Standard Deviation of } \log(t_i) = B_2 + B_3\log(D),\end{array}\right\}. \quad (5)$$

where B_0, B_1, B_2 and B_3 are constants whose values depend on the type of material and of loading the conditions (i.e., constant load or varying loads), and are evaluated by applying the procedures of laboratory curves fitting to real data. For austenitic stainless steel AISI 316 NG under a constant load, Harris and al. [12] give the following values in table 2:

Table 2: B_0, B_1, B_2 and B_3 values for austenitic stainless steel AISI 316 NG [12].

B_0	-7.72
B_1	-5.39
B_2	0.32744 if log (D) < -3.96
	-0.7461 if -3.96 ≤ log (D) ≤ -3.32
	0.16056 if log (D) > -3.32
B_3	0 if log (D) < -3.96
	-0.2731 if -3.96 ≤ log (D) ≤ -3.32
	0 if log (D) > -3.32

Cracks propagation. It is assumed that the initiated cracks will grow at a constant rate (initiation rate, ν_1) until conditions are appropriate for the treatment of cracks propagation with fracture mechanics. ν_1 statistical properties are determined using expressions given in M-PRAISE, through correlations expressed as a function of the damage parameter D.

To take into account considerable dispersion in ν_1 observed during the experiments, this latter is considered as a random variable following a log-normal distribution for a given value of D.

Although the standard deviation of ν_1 is independent of D, the mean value of log (ν_1) changes linearly with log (D), and is given by the following relationship:

$$\log(\nu_1) = F + G \log(D). \quad (6)$$

where F is normally distributed, and G is a constant. For austenitic stainless steel AISI 316 NG, F has a mean value of - 0.02266 and a standard deviation of 0.2052, and G = 0.63136.

The procedure for the transition from initiation to propagation used by fracture mechanics is presented as follows [12]:

- Pre-existing cracks always grows according to the rate of fracture mechanics.
- The initiation rate is always assigned to initiate cracks.
- At any time, if the rate of fracture mechanics ν_2 is greater than the initiation rate, and the crack depth is greater than 0.1 (in) (1 (in) = 25.4 (mm)), this crack especially grows at the fracture mechanics rate thereafter.
- If the stress intensity factor for a crack is negative, the crack will not grow.

The crack propagation rate ν_2 (inches/year) is given by the equation Eq. (7):

$$\log(\nu_2) = C_{14} + C_{15} D_k. \quad (7)$$

where D_k is the damage parameter given by the following equation :

$$D_k = C_{12} \log[f_2(\text{environment})] + C_{13} K. \quad (8)$$

where K is the stress intensity factor, C_{12}, C_{13}, C_{15} are constants and C_{14} is normally distributed. For the austenitic stainless steel AISI 316 NG [14] (see Table 3)

Table 3: C_{12}, C_{13}, C_{14} and C_{15} values for austenitic stainless steel AISI 316 NG [12].

C_{12}	0.8192
C_{13}	0.03621
C_{14}	Mean value = - 4.006 Standard deviation = 0.5792
C_{15}	1.19

Crack size at the initiation. In PRAISE, shape of surface crack initiated due to IGSCC is considered to be semi-elliptical (Fig.1), which is also consistent with shapes of stress corrosion cracks reported by Helie [7] and by Lu [8]. For these analyses, it was assumed that the geometric shape of the initial crack, i.e., semi-elliptical for surface cracks, did not change as the crack grew. Surface length of initiated cracks (l = 2b), is assumed to be log normally distributed with a median value of 3.175mm and a shape parameter of 0.85 [4,13,14]. Depth of initiated crack is taken to be 0.0254 mm.

Fracture criterion. In this study, defects can damage the pipe by (leak or fracture). Cracks can grow and become stable or unstable through the pipe thickness. The stability of the partial crack crossing the wall is verified by comparing the stress on the net section σ_{net} with the flow stress σ_f.

- ✓ Fracture criteria to have a leak :

In M-PRAISE the fracture criterion to have a leak in the pipe is a = h, where h is wall thickness and a is the crack depth. Assuming that each simulated pipe fracture considered by the process used in M-PRAISE has also been considered as a leak with Monte Carlo simulations.

- ✓ Criteria to have a total fracture :

The pipe total fracture criterion used in M-PRAISE is the collapse of the net section.

$$\sigma_{net} = \frac{\sigma_{LC} A_P}{A_P - A_{cr}} > \sigma_f . \tag{9}$$

$$A_P = \pi h \left(2R_i + h\right), \quad A_{cr} = ab\left[2 + \left(\frac{a}{R_i}\right)\right]. \tag{10}$$

where R_i is the pipe inner radius, h is the pipe wall thickness, A_p is the area of the pipe section, A_{cr} is the crack area, and are controlled components of the flow stress load respectively.

The flow stress is used in equation Eq. (9). σ_f has been considered normally distributed, with a mean value of 314 (MPa) and a standard deviation of 13.3 (MPa).

- ✓ Leak detection and quantification :

A growing defect leading to a stable wall crack is considered to have a leak potential. Supposing that the detected leak is sufficiently large, it can lead to a pipe failure. To determine if a leak is determined, it is necessary to estimate the leak rate, which required an estimation of the crack opening area.

$$\delta = \frac{4\sigma b\left(1-\nu^2\right)}{E}. \tag{11}$$

The leak rate is estimated using the expression (1 (mil): 0.0254 (mm))

$$\frac{Q h^{1/2}}{2b} = \begin{cases} 0.25\delta^2 & \text{for } \delta \le 2\text{(mils)} \\ 0.9375\delta - 0.875 & \text{for } \delta > 2\text{(mils)} \end{cases}. \tag{12}$$

where δ is the total displacement of the crack opening (mils), ν is Poisson coefficient, E is the elasticity modulus of the pipe material, σ is the applied tension, h is the pipe wall thickness, 2b is the crack length, and Q is the leak rate (gal/min).

A pipe failure will occur if the leak rate through the wall resulting from all the cracks is greater than the detectable leak rate.

Monte Carlo simulations. Monte Carlo simulations (MCS) is a mathematical technique that takes into account the risk in the quantitative analysis and the decision-making. The diverse professionals in the fields of finance, project management, energy, production, engineering, research and development, insurances, gas and oil industry, transportation and environment, have recourse to this technique.

As all numerical methods, MCS has advantages and drawbacks. One within the main advantages:

- MCS allows using explicit as well as implicit variables in the performance function. Concerning its precision;

- MCS is considered as a reference method by most researchers in the fields of structural reliability.

Application and Results Analysis

Application. The considered problem illustrates the use of M-PRAISE to simulate the initiation and the growth of cracks in a welding due to the stress corrosion cracking mechanism. The necessary material properties for the initiation and growth of cracks under SCC in AISI 316 NG steel are preselected in this case and introduced in the code. The only used loading cycle is the heating-cooling cycle. The used fracture criteria are presented in the section fracture criterion. The main input related to the pipe geometry, pipe material, and the working conditions for the basic case are described below: Table 4

Table 4: Conditions for the basic case.

Pipe geometry	Inner radius = 7.16 (in) Wall Thickness = 0.84 (in)
Loading stress	Total loading = 15.23 (ksi) Working pressure = 5250 (psi) (1 (psi) = 0.00689476 (MPa))
Material flow stress	Mean value = 44.9 (ksi) Standard deviation = 1.9 (ksi)
SCC Parameters	Oxygen at the start= 8 (ppm) Stable oxygen at steady state = 0.2 (ppm) (1(ppm) = 0.001(g/L)) Water temperature at steady state = 550 (°F) (1 °F = -17.22 °C) Heating time = 5 (hours) Cooling liquid conductivity = 0.2 (µs/cm)

A lifetime of 20 years is simulated and the results printed every two years. The maximal time step for the growth of cracks under stress corrosion cracking is limited to 0.1 year, which means that during a long period of operation at steady state, the crack size, the stress intensity factors, and other computations are updated every 0.1 year.

In the output file, there is a description of the data. Other than the initiation probability, leak probabilities as a function of time are represented in this file. Unlike the case of pre-existing cracks with a stratified sampling, the leak probability and the failure probability are obtained in the same sequence printing.

In the considered example, we have proceeded to:

1- Generation of pipe samples for the probabilistic analysis as shown in Fig. 4
2- Generation (1000 x 10 x n) times of initiations from 1000 values of the damage parameter D. (see Fig. 5)
3- Generation (1000 x 10 x n) times of initiation rates from 1000 values of the damage parameter D (see Fig. 6)
4- Computation of the cracks propagation rate based on fracture mechanics, for (1000x 10 x n) generated cracks using the values of σ, a and b. (see Fig. 7)
5- Computation of the probabilities of initiation, leak, big leak, and of failure according to the used failure criteria.

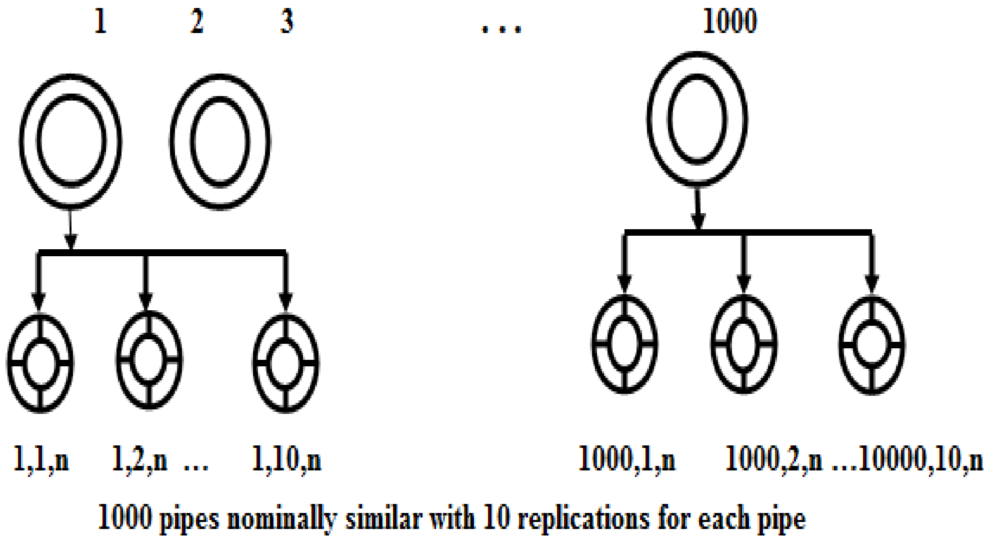

Fig. 4: Generation of tube samples for the probabilistic analysis – schematic representation.

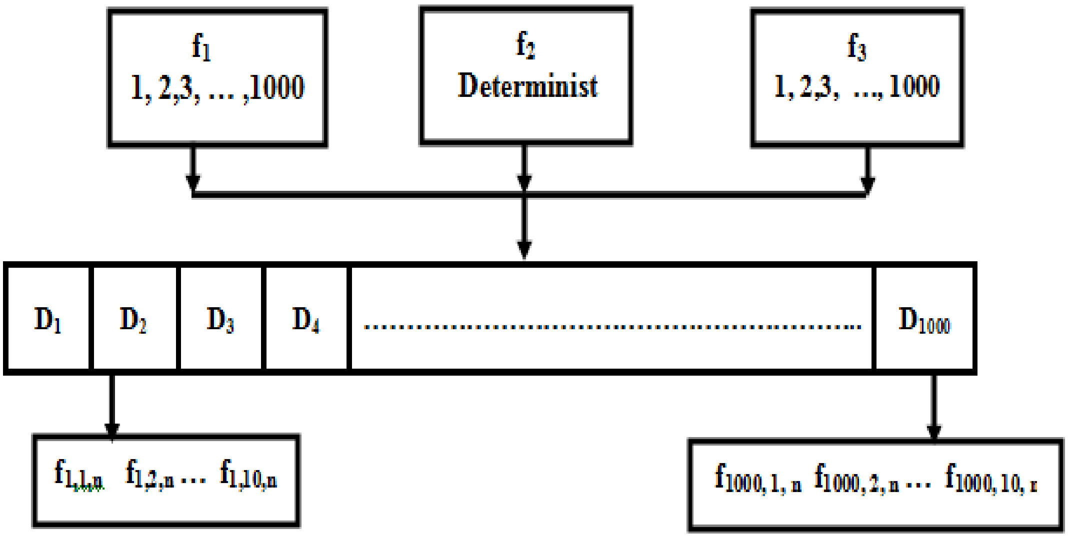

Fig. 5: Generation (1000 x 10 x n) times of initiations from 1000 values of the damage parameter.

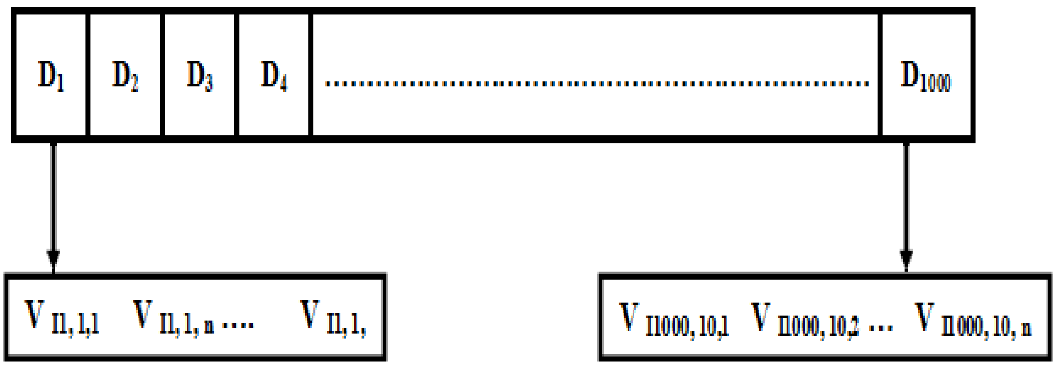

Fig. 6: Generation (1000 x 10 x n) times of initiation rates from 1000 values of the damage parameter, D

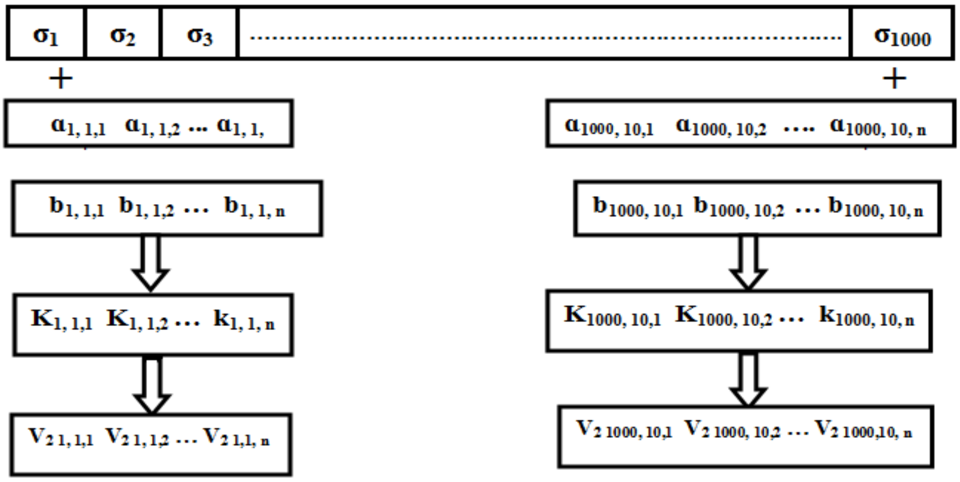

Fig. 7: Computation of the cracks propagation rate based on fracture mechanics, for (1000 x 10 x n) generated cracks using the values of σ, a and b.

Results analysis. A variety of metallic materials are fabricated by different processes was that the extent of the degradation involves complex interactions between the various metallurgical, environmental and stressing parameters, and this becomes of critical importance when considering localized corrosion. The complexity of these interactions is discussed below, using as an example the initiation and growth of a stress corrosion or corrosion fatigue crack, as illustrated schematically in Fig.8.

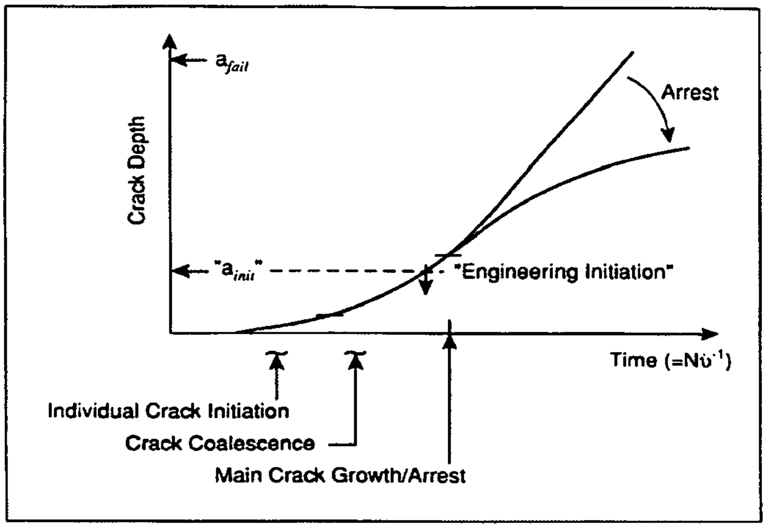

Fig. 8: Sequence of crack initiation, coalescence and growth during subcritical cracking in aqueous environments [15]

In this case, cracks can initiate on a microscopic level at surface inhomogeneities associated with fabrication or design defects such as scratches, cold worked regions or weld defects, or at corrosion-based artifacts such as pits. The micron-sized cracks that initiate from these individual surface imperfections may grow or arrest, dependent on the specific material, stress and environment conditions. They may then coalesce, depending on the geometric spacing of the microcracks to form a larger crack. The resultant crack will only be detectable in an engineering structure when its depth is considerably greater, dependent on the specifics of the inspection technique.

In some cases, the initiation of microcracks may start very early in life at preexisting surface inhomogeneities such as scratches. In other cases the sequence of events illustrated in Fig.8 may be deferred for many years due to the formation of a specific localized chemistry in a crevice, or the development of a "susceptible" material microstructure due to the accumulation of a specific amount of irradiation fluence.

Assuming that the local conditions are met for the sequence of events in Fig.8 to proceed, it can be argued that the physical process of cracking should exhibit an inherent variance and be appropriately analyzed in a probabilistic manner, since it has been shown that the processes that control the early crack initiation process, such as pitting, intergranular attack and crack coalescence, are stochastic phenomena. Thus, Akashi and al. ([16] and [17]) indicate (Fig. 9) that crack initiation times (engineering) may be predicted by such a probabilistic approach.

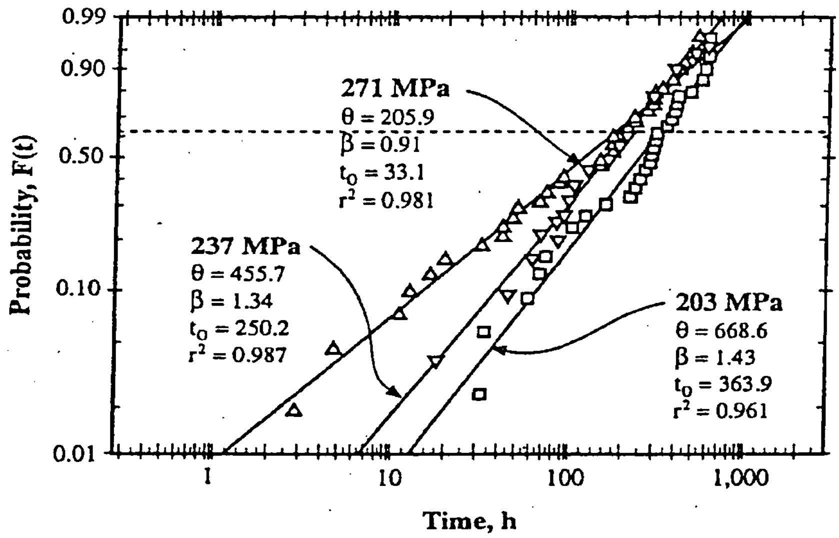

Fig. 9: Probability vs. time for initiation of stress corrosion cracks in sensitized stainless steel in 288°C, 8ppm oxygenated water [17]

It is apparent that the extent of observed damage accumulation is reasonably predicted by theoretical trend lines that were developed via an understanding of the mechanism of cracking [17]. This is illustrated in Fig.10.

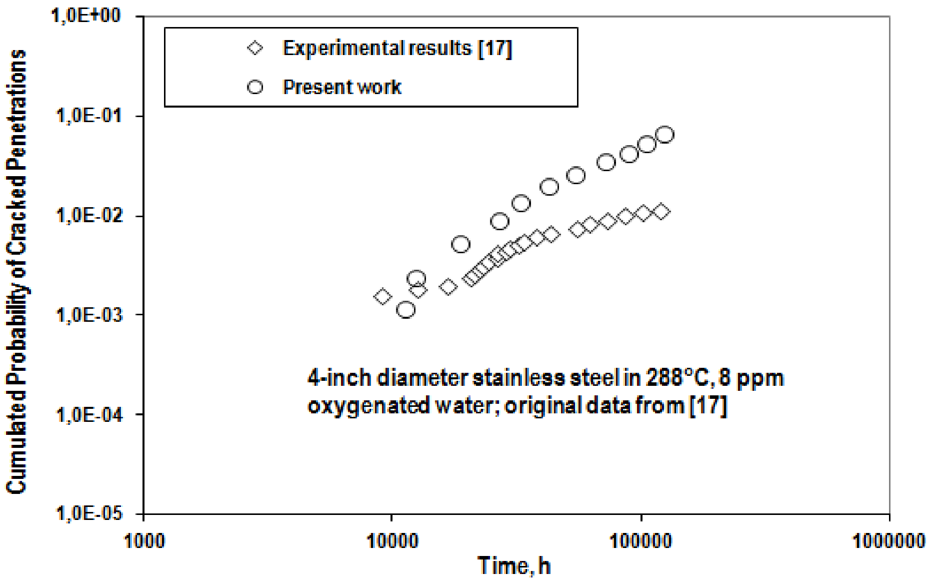

Fig. 10: Probability vs. time for initiation of stress corrosion cracks in sensitized 4-inch diameter stainless steel in 288°C, 8 ppm oxygenated water; original data from [17]

The object of this work is the study of the influence of the modification of the parameters characterizing the environment and particularly the change in the oxygen concentration, and in the temperature during the operation.

Effects of the change in the oxygen concentration. For a temperature of 550 (°F), Table 5 resumes the used steady state oxygen concentrations to illustrate the effect of their variation.

Table 5: Studied cases

Studied case	Case1	Case12	Case13	Case14	Case15
Oxygen concentration (ppm)	0.2	0.05	0.01	0.1	1

Fig. 11 presents some information on the number of the initiated cracks at the beginning of the time increment during the experiment (first number of cracks), and Fig. 12 presents the number of the initiated cracks in the time increment (total initiated cracks: initiation and coalescence). These results are printed at each evaluation time for case1, case12, case13 and case14.

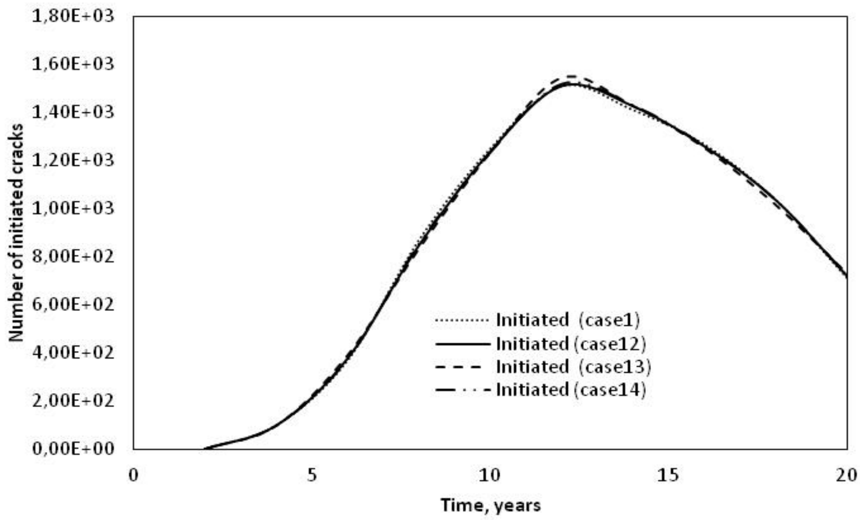

Fig. 11: Predicted percentage of initiated cracks.

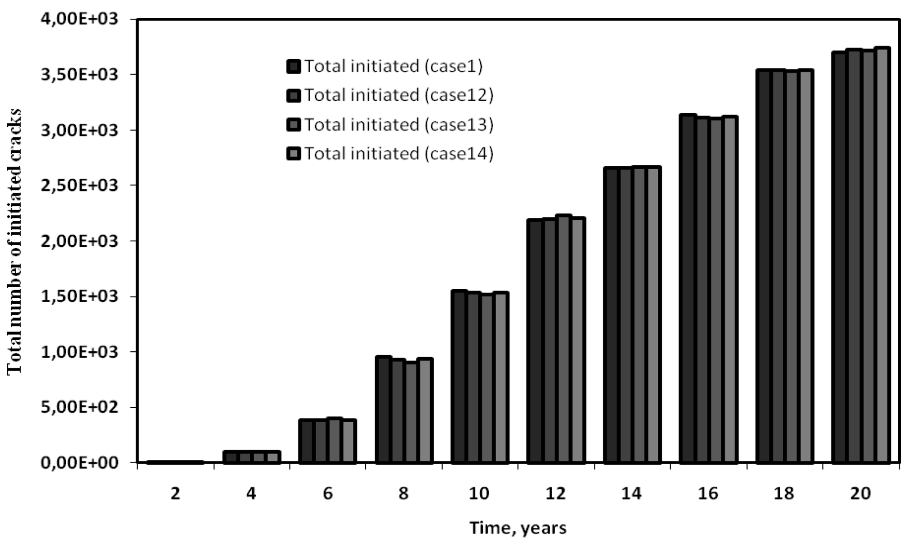

Fig. 12: Total number of initiated cracks with time.

For a given value of the damage D, Figs (13 to 15) show the probability of failure as a function of time. Hence besides the crack initiation probability, the probability of a leak (crack crossing the wall) is evaluated for the 4 cases (1, 12, 13 and 14) respectively.

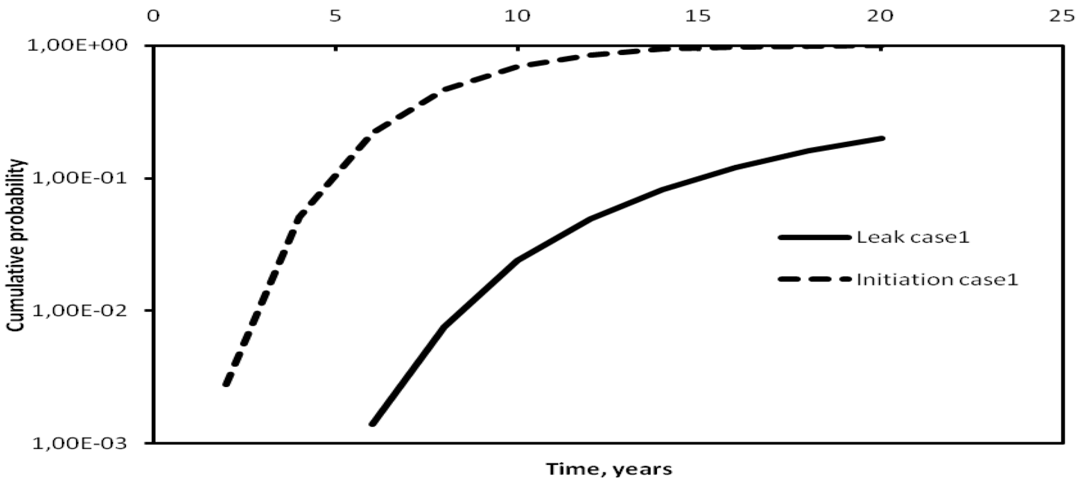

Fig. 13: Initiating and to have a leak probability (case1).

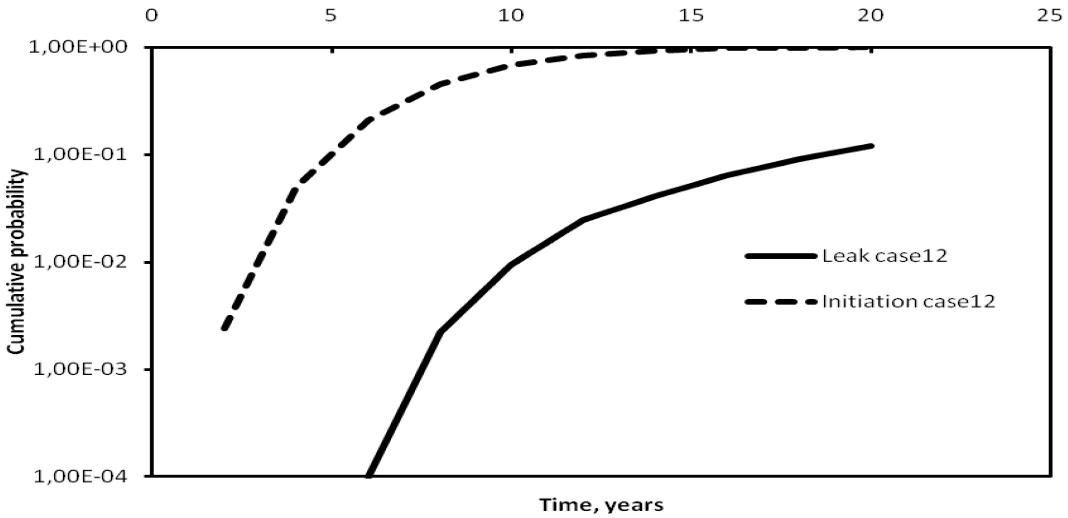

Fig. 14: Initiating and to have a leak probability (case12).

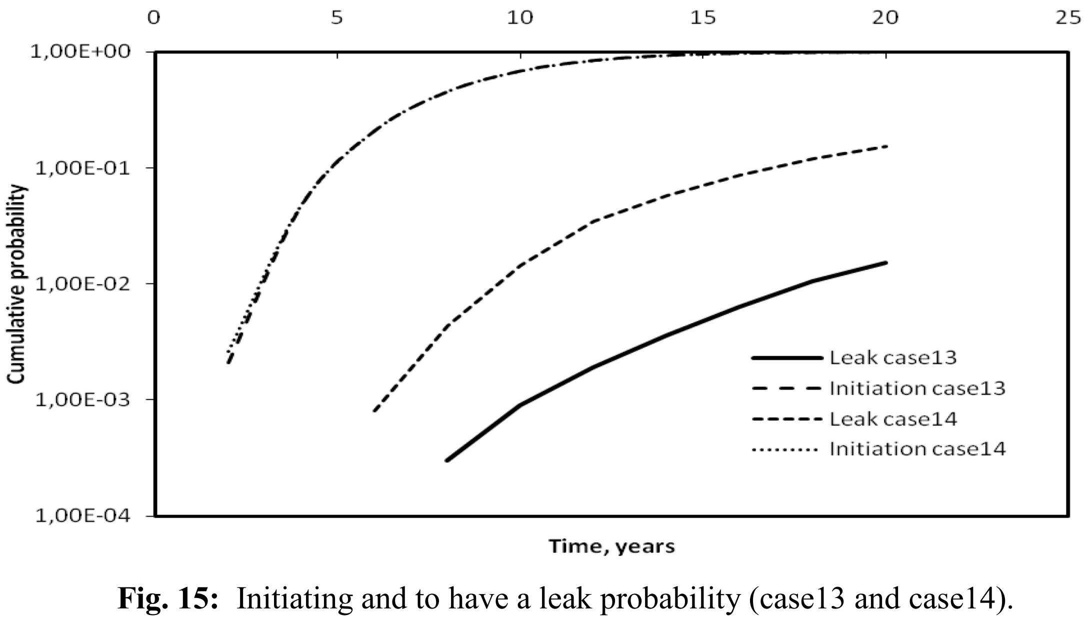

Fig. 15: Initiating and to have a leak probability (case13 and case14).

For weak damages (Fig. 16) the variation of oxygen concentrations does not affect the initiation process (Fig. 17).

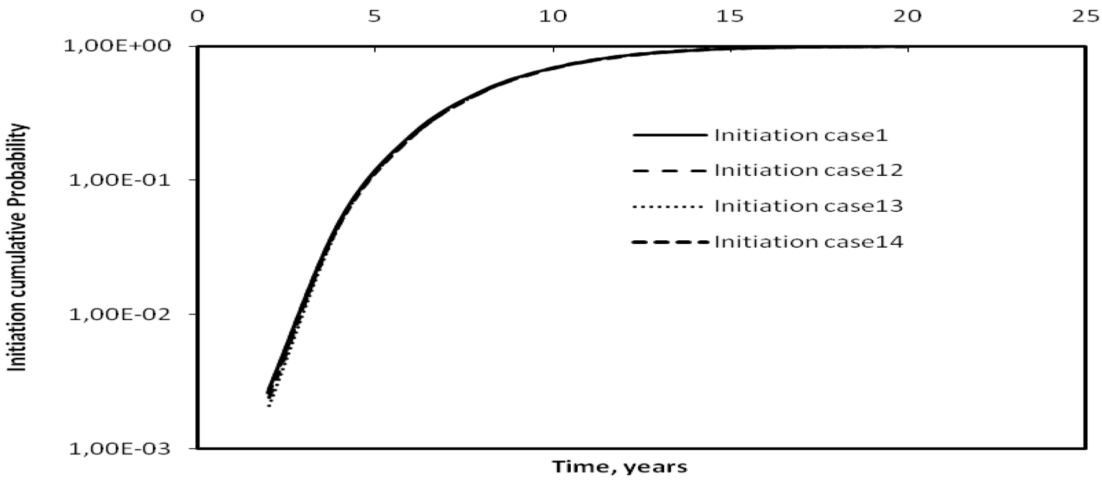

Fig. 16: Probability to initiate cracks (case 1, case12, case13 and case14).

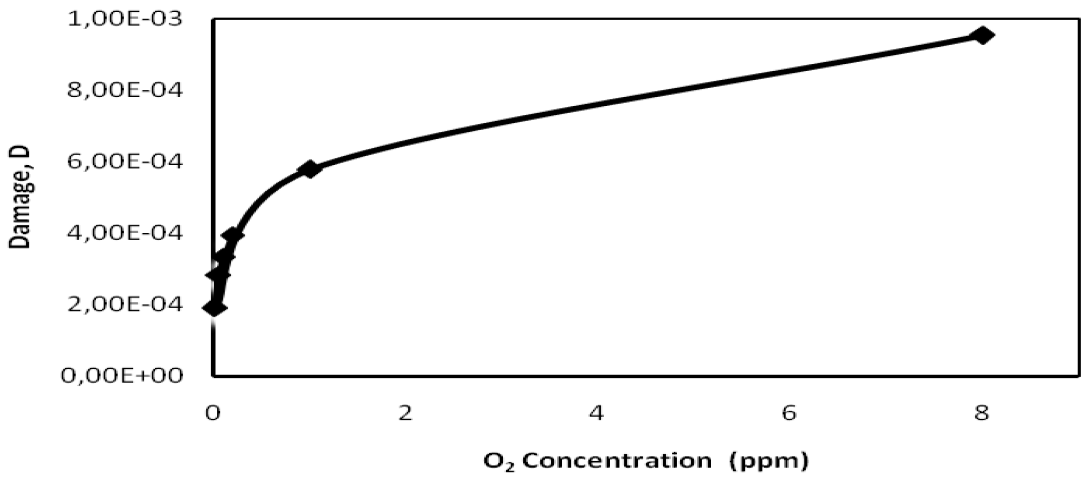

Fig. 17: Damage versus O_2 concentration.

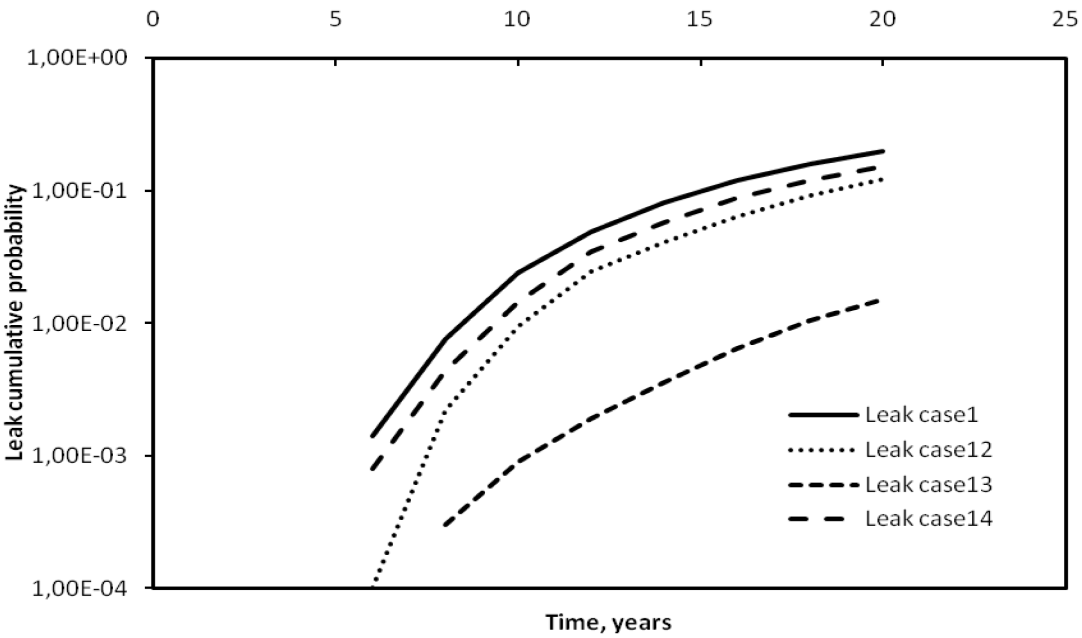

Fig. 18: Probability to have leak (case1, case12, case13 and case14).

Fig. 18 regroups the leak cumulative probabilities for the treated examples. If we suppose that cas1 is a reference (O_2 concentration = 0.2(ppm)) one notes that when the transient regime concentration is approached (case14: O_2 concentration = 0.1(ppm)) the leak probability is amplified 1.31 times. And when we are below the transient regime concentration (case13: O_2 concentration = 0.01(ppm)) the leak probability is reduced 10.09 times.

Effects of temperature change. For an oxygen concentration of 0.2 (ppm), Table 6 resumes the temperatures used to illustrate the effect of their variations.

Table 6: Temperatures used and cases studied

Studied case	Case 1-550	Case 12-560	Case 13-479	Case 14-480	Case 15-450
Temperature (°F)	550	560	479	480	450

Fig. 19 regroups the initiation probability curves for the 5 cases studied. Results are printed at each evaluation time for case1-550, case12-560, case13-479, case14-480 and case15-450. For weak damages (Fig. 20) the variation of temperature does not affect the initiation process (Fig. 21).

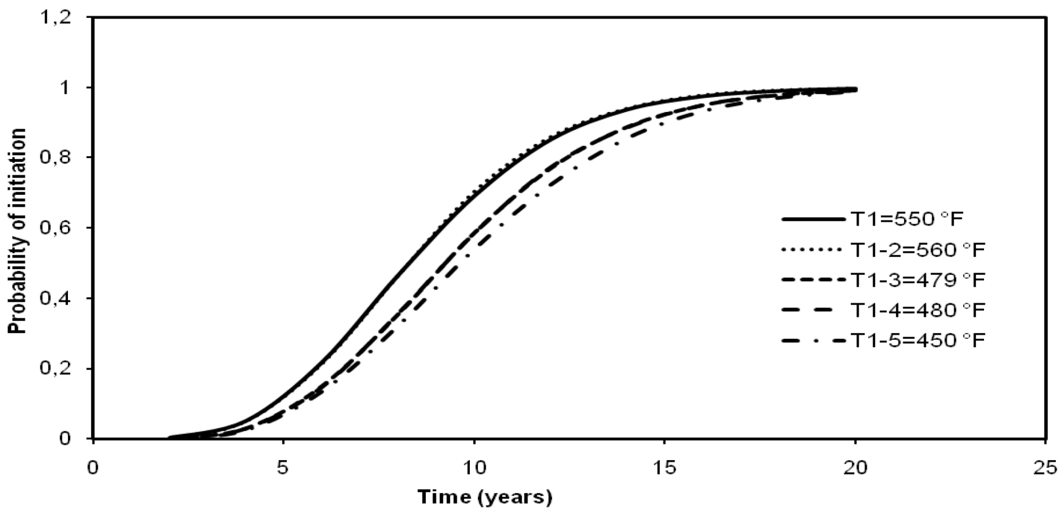

Fig. 19: Probability of initiation for different temperature.

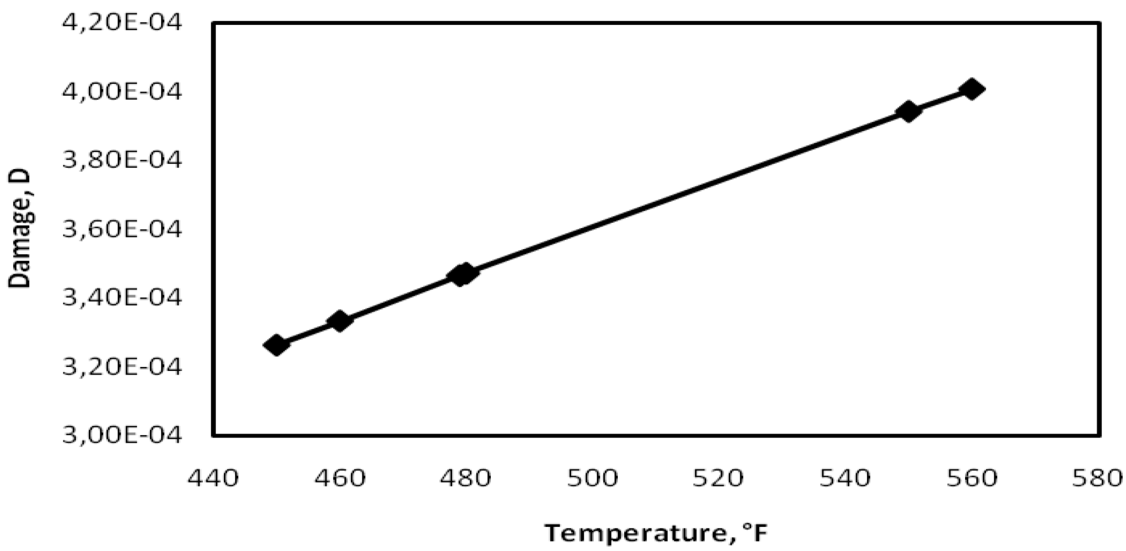

Fig. 20: Damage versus temperature.

Fig. 21 regroups the leak probability curves for the 4 cases studied. The effect of temperature depends on the triggering temperature of the Heat-up and Cool-down cycle.

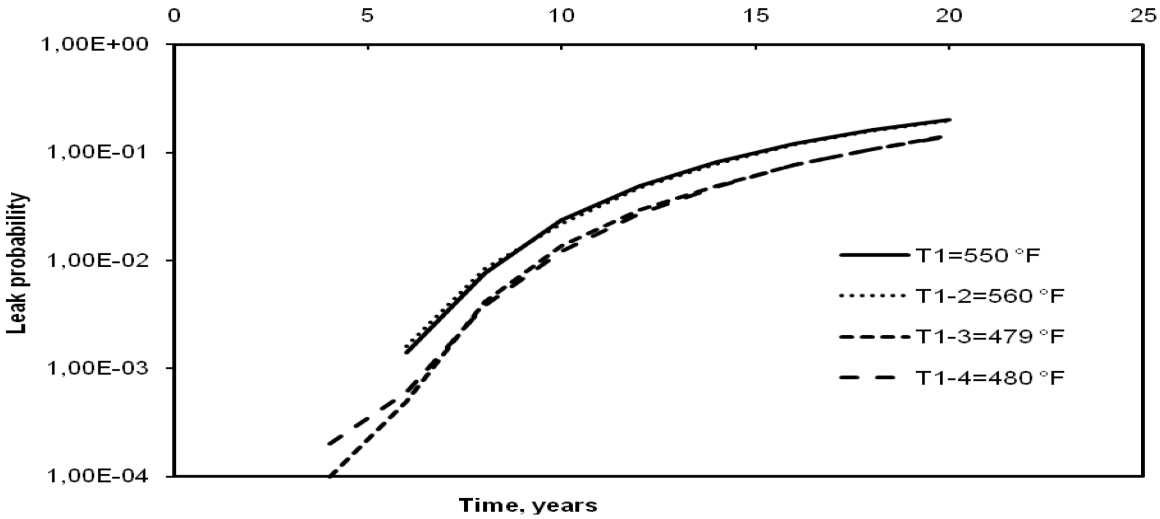

Fig. 18: Effect of temperature on leak probability.

Summary

Many reliability problems of industrial structures are related to the presence of cracks, which under certain loadings can lead to their ruin. Characterisation of the harmfulness of this type of defect is essential to know, among other things, the residual lifetime of cracked structures. In the domain of under pressure equipment, the operating safety under all circumstances is omnipresent, and characterisation of defects harmfulness is essential. To partly answer this problem, fracture mechanics coupled with numerical methods has been used in this work. Models based on probabilistic fracture mechanics of structures are used more and more to predict the reliability of under pressure components of nuclear installations such as welding's in piping systems [1-2] and nuclear reactor pressure vessels [3].

The use of a model to predict and analyse the reliability of under pressure pipes based on fracture mechanics by means of M-PRAISE computation program upgraded over the last few years to allow checking initiation and propagation of cracks in a variety of materials for under pressure piping and in boiling water reactors.

The subroutine of initiation has been used in conjunction with Monte Carlo Simulation to estimate the probability of failure as a function of time. In addition to the probability of initiation of cracks, the probability to have a leak in the piping has been evaluated. The study and the analysis of the results obtained from the treated cases show the influence of the variation of the environmental parameters on leakage probability. Most figures present statistics on initiated cracks as a function of time. Many cracks are predicted to initiate, but none could grow to become a trough-wall crack during the pipe lifetime, which is simulated to 20 years. Lastly, for small damages we observed that the change in temperature or oxygen concentration does not affect the initiation process but their decrease contribute favourably to the decrease in the leakage probabilities.

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