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Impact of In-Service Inspection on the Reliability of Small Piping

Abdelmoumene GUEDRI[1,a*] Moammed Amine BELYAMNA[1,b],
Racim BOUTELIDJA[1, c]

[1]Department of Mechanical Engineering, INFRA-RES Laboratory, MCM-Souk Ahras University,
Souk Ahras, Algeria

[a*]guedri_moumen@yahoo.fr, [b]beelyamina@gmail.com, [c] boutelidja.racim@gmail.com

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Abstract. This paper describes the cracking of stainless steel piping under Inter-granular Stress Corrosion Cracking (IGSCC) conditions using probabilistic fracture mechanics that predict the impact of in-service inspection (ISI) programs on the reliability of specific nuclear piping systems that have failed in service. The IGSCC is characterized by a single damage parameter, which depends on residual stresses, environmental conditions, and the degree of sensitization. The Probability of Detection (POD) curves and the benefits of in-service inspection in order to reduce the probability of the leak for nuclear piping systems subjected to IGSCC were discussed. The results show that an effective ISI requires a suitable combination of crack detection and inspection schedule. An augmented inspection schedule is recurred for piping with fast-growing crack to ensure that the inspection is done before the cracks reach critical sizes and that the use of a better inspection procedure can be more effective than a tenfold increase in the number of inspections of inferior quality.

Introduction

The purpose of this paper is to apply probabilistic fracture mechanics to analyze the influence of In-Service Inspection on austenitic stainless steels piping structural reliability using a single damage parameter. Several papers in the literature addressed the probabilistic failure analysis of components subjected to SCC [1-2]. Failure probabilities of a piping component subjected to SCC, including the effects of residual stresses, was computed by Guedri et al. using Monte Carlo Simulation techniques [3-4].

In this study, the simulation of stainless steel piping cracking under IGSCC conditions is based on the general methodology recommended in the Piping Reliability Analysis Including Seismic Events (PRAISE) computer program [5], which is explained briefly in the next section. The proposed procedure to quantify the reductions in failure probabilities that can be achieved with various In-Service Inspection (ISI) strategies is outlined in (cf. In-service inspection model, below). Details of numerical examples including the benefit in-service inspections considered to evaluate the structural reliability and to identify most effective approaches to improving piping reliability are presented in (cf. Numerical examples**)**, followed by **r**esults and discussions.

Probabilistic SCC Model

In this section, the methodology recommended in PRAISE for modelling IGSCC in stainless steel pipe is presented and all cracks are two-dimensional semi-elliptical interior surface cracks, generally circumferentially oriented, as shown in Fig.1. PRAISE separates the overall time to pipe leaks into three steps [5]:

a) Time to initiate a very small crack,
b) Time spent growing small cracks at an initiation velocity ν_1,
c) Time spent growing larger crack at fracture mechanics velocity ν_2 to become through-wall cracks.

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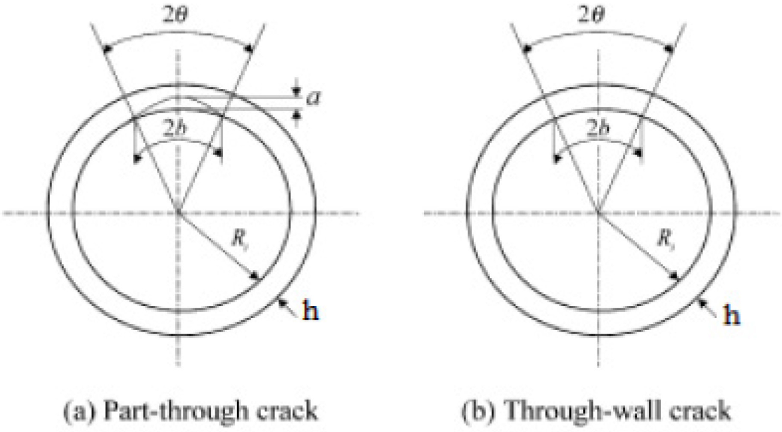
The time to crack initiation under static load conditions has been found to be a function of the damage parameter D_σ as presented in Eq. 1. The damage parameter D_σ represents the effects of loading, environment and material variables on IGSCC and is given by:

$$D_\sigma = f_1(\text{material}) \times f_2(\text{environment}) \times f_3(\text{loading}). \tag{1}$$

The growth of very small cracks that have just initiated cannot be treated from a fracture mechanics standpoint. In their work, Priya and all [6] concluded that equations used in PRAISE to calculate the stress intensity factors in order to simulate crack propagation need modification. In our modified PRAISE (M-PRAISE) [7], this modification has been accomplished using well-accepted expressions given in the ASM Handbook [8].



(a) Part-through crack (b) Through-wall crack

Fig. 1: Geometry of the part-through circumferential crack considered

In this study, cracks can fail the pipe by either breakage or leakage. The part-through initial stress corrosion cracks considered can grow and become unstable part-through cracks or stable or unstable through-wall cracks. The stability of the part-through or through-wall crack is checked by comparing net-section stress with the flow stress of the material. The failure criterion for pipe leakage used in the M-PRAISE code was a = h, where h is the wall thickness and a is the crack depth.

In-Service Inspection Model

The piping reliability model was developed on the basis of PFM concepts. The computational procedure for the estimation of leak probability combines various random variables, such as initial crack size distribution, crack detection probability, crack growth relation, and the deterministic stress history. As indicated by Fig. 1, the computation starts with the initial size of crack-like defects at a given location. These growing cracks are detected with a certain probability during pre-service and in-service inspections. Cracks that escape detection and repair can grow following subcritical crack growth characteristics such as stress corrosion cracking. The critical crack size for the leak can be defined by using an appropriate criterion. The probability of a leak at the pipe location analyzed is equal to the probability of a crack growing to corresponding critical size within the specified time. The Monte Carlo method was used in the numerical simulation. It is obvious that crack detection capability and inspection time influence the leak probability results because they are the last elements to prevent pipe leak once the crack grows in the simulation [7]. The Non-Destructive Examination (NDE) NDE experts [9-10] were asked to define POD curves by:

$$P_{ND} = \varepsilon + \frac{1}{2}(1 - \varepsilon)\,\text{erfc}\left[v\ln\left(A/A^*\right)\right] \tag{2}$$

where P_{ND} is the probability of non-detection, A is the area of the crack, A* is the area of crack for 50% P_{ND}, ε is the smallest possible P_{ND} for very large cracks, and ν is the ‘slope’ of the P_{ND} curve.

Table 1 summarizes the input data for the above three POD curves. These particular curves assume that POD is a function of the crack depth as a fraction of the pipe-wall thickness, independent of the actual wall thickness.

Table 1: POD Curve parameters for three performance levels [7]

Inspection Performance Level	a*/h(+)	ε	ν
POD01: Good	0.65	0.25	1.40
POD02: Very Good	0.40	0.10	1.60
POD03: Advanced	0.15	0.02	1.60
(+) h is the wall thickness of the pipe.			

Numerical Examples

Table 2 summarizes the input parameters for the calculations. Base case (no ISI) M-PRAISE runs were first.

Table 2: Input values of SCC parameters and pipe loading including the effects of ISI

Outside diameter, [mm] Wall thickness, [mm]	89 8.6
Initial flaw distribution, [mm]	Log normal distribution Deterministic flaw depth = 0.025 Mean flaw length = 3.2 Shape parameter = 0.85
Pipe loading values [MPa]	Stress due to cold =6.65 Stress due to thermal = 49.5 Operating pressure (OP)= 9.31 Stress due to OP =24.01 Stress due to DWT+THML+OP.PRES = 80.16
SCC Parameters	O_2 at startup [PPM] = 8.00 O_2 at steady state (PPM] = 0.20 Temp. at steady state [°C] = 293.33 Heat up (38-260[°C]) Time [HRS] = 5.00 Coolant conductivity [μ S/cm] = 0.20
Flow stress of piping material, [MPa]	Normal distribution Mean = 296 and Standard deviation = 29
Welding residual stress, [MPa]	Randomized M-PRAISE input values for small lines with adjustment of: f = 0.75, Stress at ID: Mean = 168, SD = 100
POD Curves	Three (3) POD Curves as per table 1
Frequency of inspection, [yr], (Time of initial ISI/ Frequency)	10/10, 4/4, 2/2 and 1/1

These calculations assumed realistic ranges for the various input variables that govern the initiation and growth of IGSCC cracks. The following variables were addressed: O_2 content, temperature, coolant conductivity, applied stress and frequency of heat up and cool down. This initial set of M-PRAISE runs assumed no in-service inspection and gave calculated 40-year cumulative leak probabilities. The second phase of the calculations included simulations of in-service inspection for a range of POD curves and inspection frequencies as indicated in Table 2. The failure probability P_f is calculated using MCS techniques as

$$P_f = N_f / N \,. \tag{3}$$

Where N_f is the number of failure cases and N is the total number of simulations.

Results and Discussion

This section presents a collection of plots that show trends for pipe-leak probabilities and for the effectiveness of various ISI strategies in leak probabilities using the input data presented in Table2.

Fig.2 provides a plot of these probabilities for times extending to 40 years. It can be seen that, when compared with the case of no inspection, the reliability of the pipe is not improved significantly by the good team's inspection, even with an augmented inspection program such as schedule ISI (10/10).

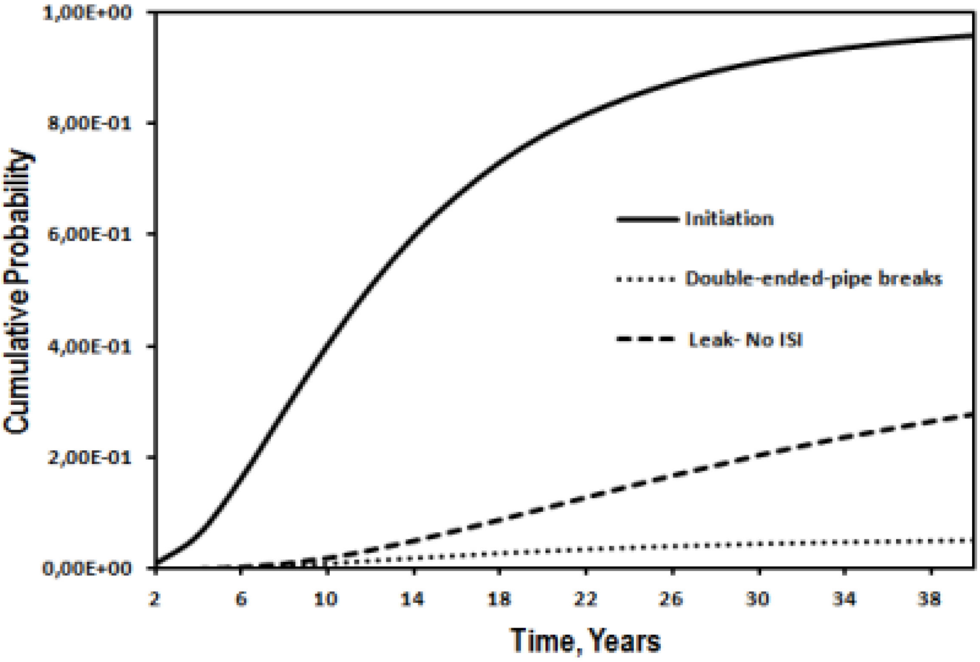


Fig. 2: Cumulative Failure Probability as Functions of Time

Fig.3 shows the predicted leak probability over 40-year plant life for the good (POD01) inspection teams and the four inspection schedules.

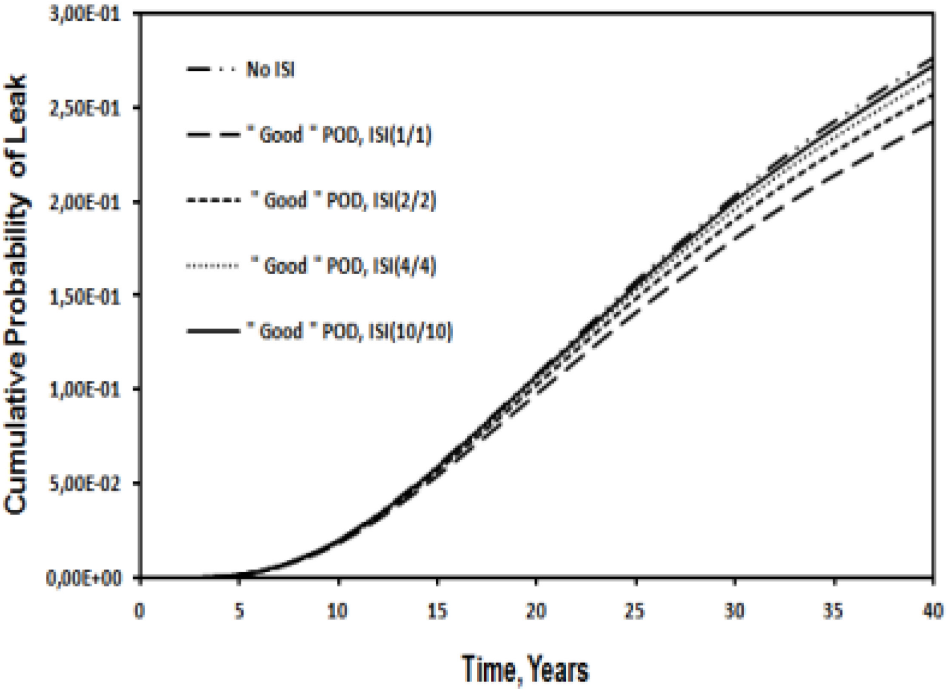


Fig. 3: Cumulative Leak Probability Based on good (POD01) Inspection Team and Four Inspections

However, both very good (POD02) and an advanced (POD03) inspection teams provide an improvement and reduce leak probabilities, as shown in Fig.4 and Fig.5 respectively. POD02 inspection team can cat the leak probabilities from 0.277 for no ISI to 0.124 (schedule ISI(1/1)) at the end of plant life. With the help of POD03 team, the leak probabilities become 0.141 (schedule ISI(10/10)), 0.082 (schedule ISI(4/4)), 0.054 (schedule ISI(2/2)), and 0.037 (schedule ISI(1/1)) at the end of plant life.

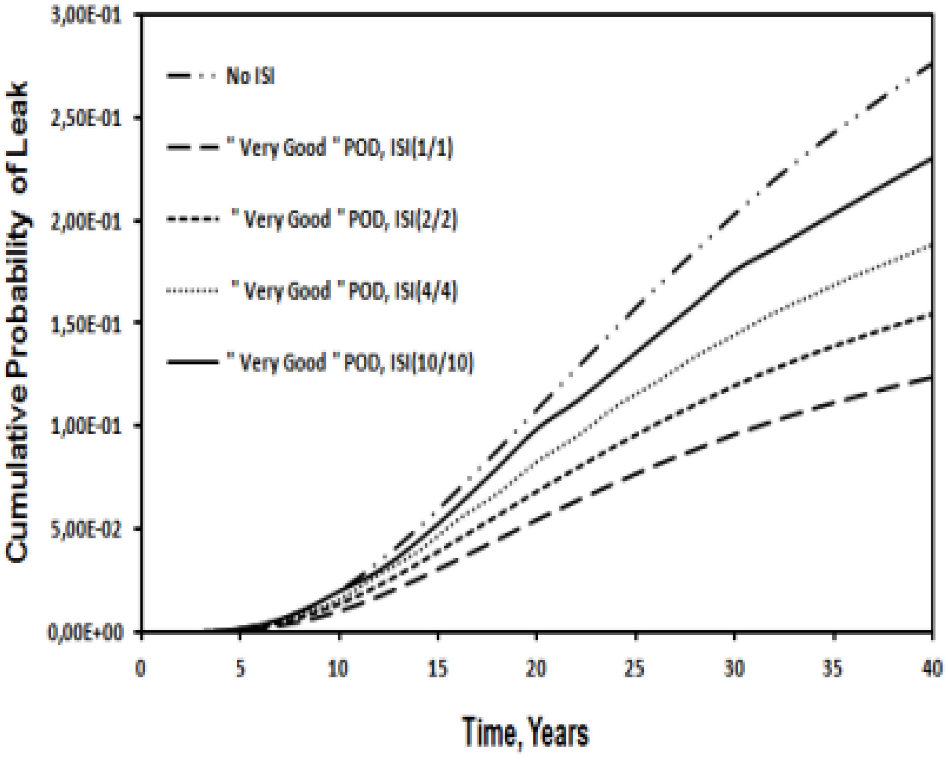


Fig. 4: Schedules Cumulative Leak Probability Based on very good (POD02) Inspection Team and Four Inspection Schedules

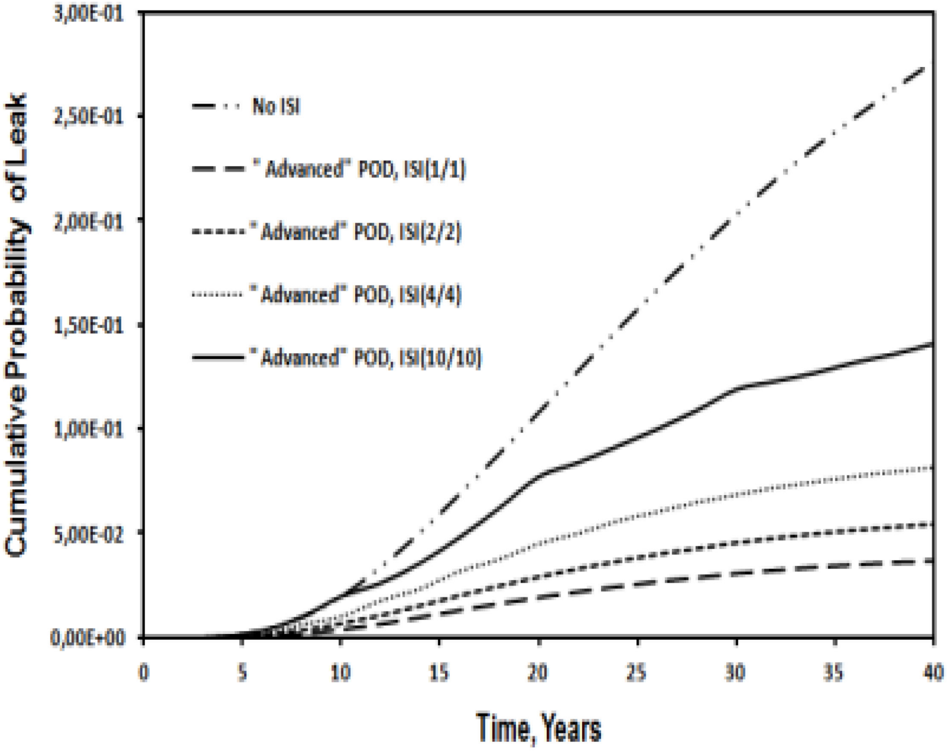


Fig. 5: Cumulative Leak Probability Based on an advanced (POD03) Inspection Team and Four Inspection Schedules

In Fig. 6 the results indicate that the use of a better procedure can be more effective than a tenfold increase in the number of inspections with the continued use of an inferior procedure.

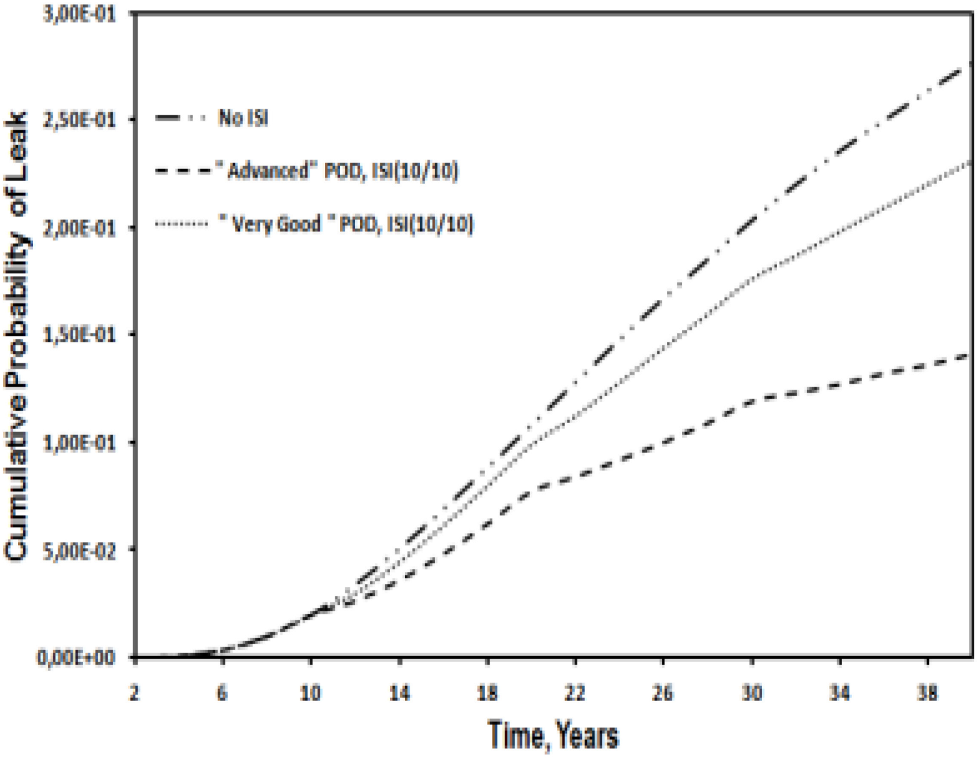


Fig. 6: Impact of inspection procedures

Results presented in Fig. 7 show a good correlation between 40-year cumulative leak probabilities and D_σ. this parameter does provide a useful basis to generalize results for piping-leak probabilities.

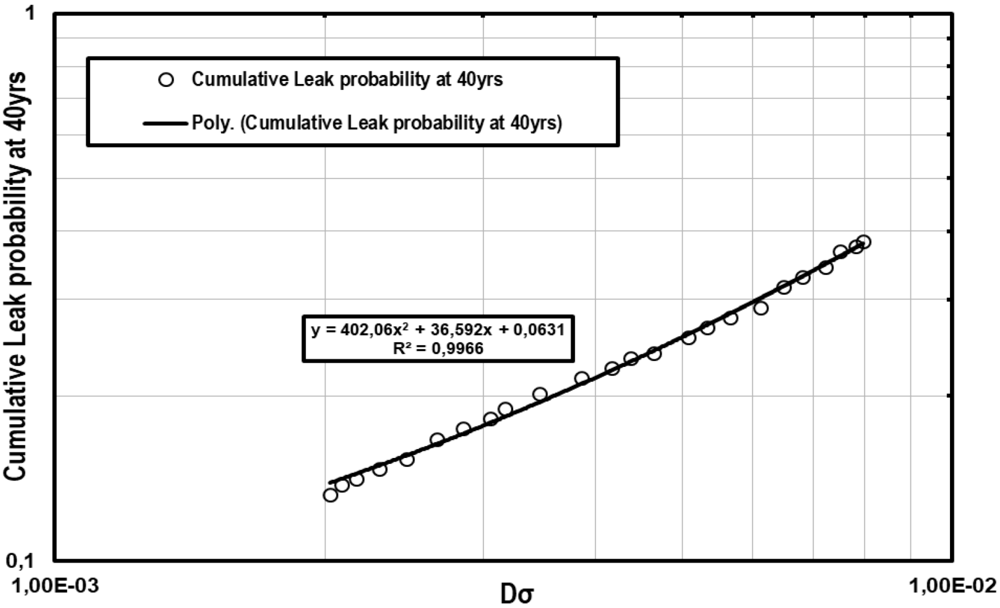


Fig. 7: Cumulative Leak Probability Over 40 Years as a Function of the Stress-Corrosion Damage Parameter D_σ [10].

Fig. 8 to Fig.9 show predicted improvements in reliability over a 40-year design life for pipe that results from ISI performed over the 40-year operating period and describes inspections performed at a Y-year interval and with the first inspection at the Xth year using the notation X/Y. Three different levels of NDE performance are addressed the inspection method was held constant, and the inspection intervals ranged from 1 to 10 years with the curves rearranged to maintain a common inspection interval for each plot, with the individual curves corresponding to different POD curves. Better inspection procedures (POD02 versus POD01 and POD03 versus POD02) appear to offer a cost-effective option for enhancing piping performance.

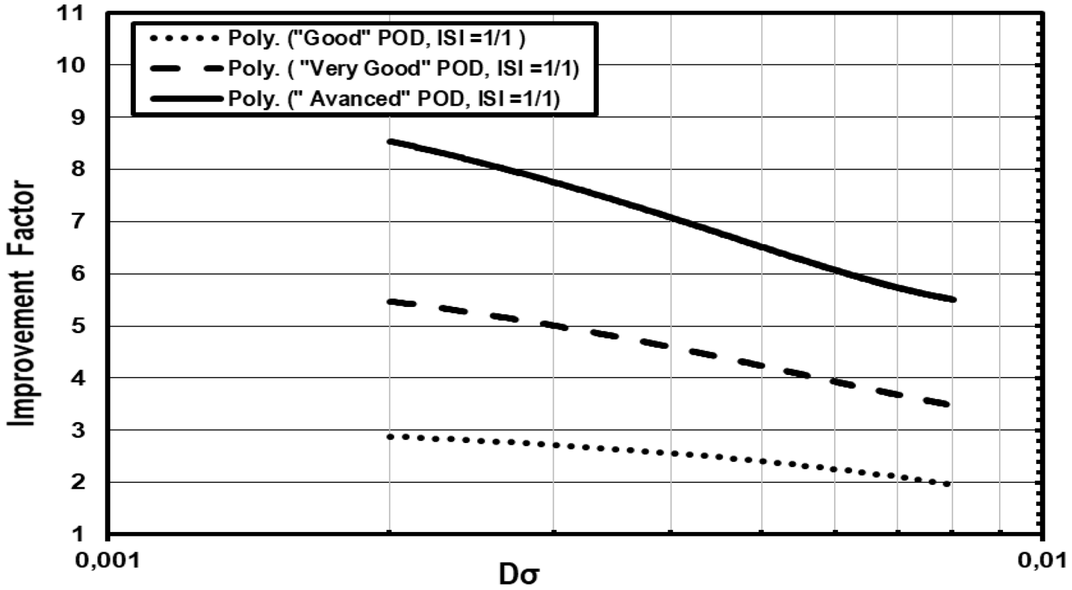


Fig. 8: Improvement Factors versus D_σ for 1-Year ISI Interval with various POD Curves

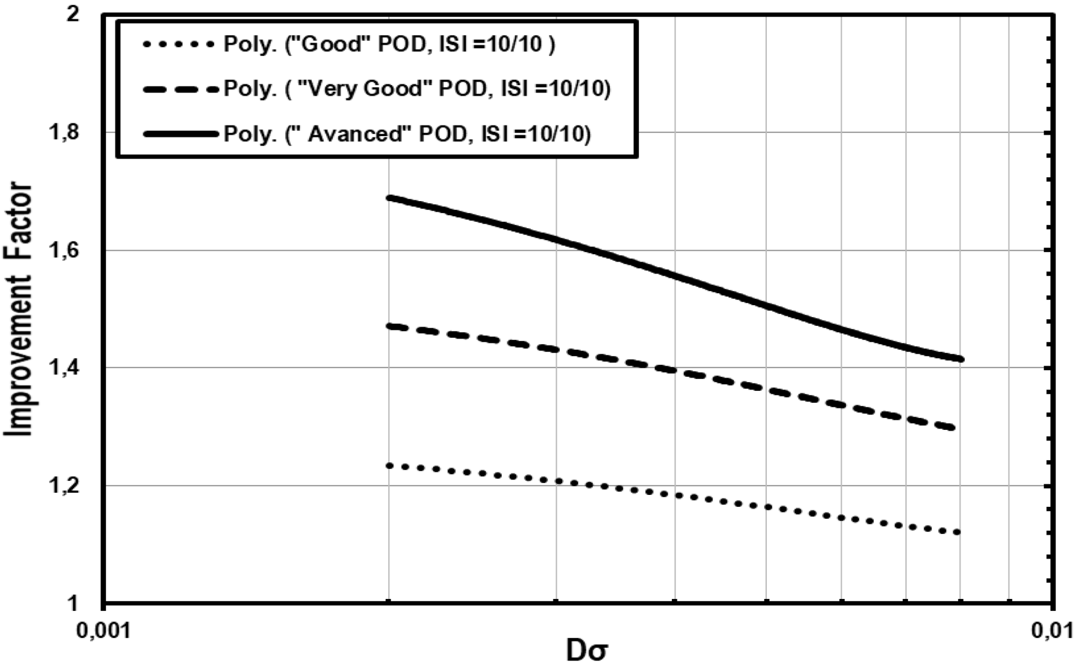


Fig. 9: Improvement Factors versus D_σ for 10-Year ISI Interval with various POD Curves

Summary

Our model was used to predict the probability of failure of different level of pipe damages and was applied to assess the effect of various inspection scenarios on leak probabilities. This chapter has also discussed the POD curves and the benefits of ISI in the framework of reductions in the leak probabilities for nuclear piping systems subjected to IGSCC. The results for typical NDE performance levels indicate that low inspection frequencies can provide only modest reductions in failure probabilities. More inspections that are frequent appear to be even more effective. However, using POD03 the NDE reliability can achieve a factor of 10 improvements in preventing IGSCC leaks at typical operating conditions even when inspections occur approximately every 10 years; this can be increased to a factor even greater than 10 if the inspection interval is decreased sufficiently.

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