

PREDICTING THE PROBABILITY OF FAILURE OF GAS PIPELINES INCLUDING INSPECTION AND REPAIR PROCEDURES

Zhang, L.¹, Adey, R.A.²

¹ C M BEASY Ltd, Ashurst Lodge, Lyndhurst Road, Southampton, SO40 7AA, UK,
lzhang@beasy.com

² C M BEASY Ltd, Ashurst Lodge, Lyndhurst Road, Southampton, SO40 7AA, UK,
r.adey@beasy.com

ABSTRACT

This paper is concerned with predicting the impact on the probability of failure of adding hydrogen to the natural gas distribution network. Hydrogen has been demonstrated to change the behaviour of crack like defects which may affect the safety of pipeline or make it more expensive to operate. A tool has been developed based on a stochastic approach to assess the failure probability of the gas pipeline due to the existence of crack-like defects including the operational aspects of the pipeline such as inspection and repair procedures. With various parameters such as crack sizes, material properties, internal pressure modelled as uncertainties, a reliability analysis based on failure assessment diagram is performed through direct Monte Carlo simulation. Inspection and repair procedures are included in the simulation to enable realistic pipeline maintenance scenarios to be simulated. In the data preparation process, the accuracy of the probabilistic definition of the uncertainties is crucial as the results are very sensitive to certain variables such as the crack depth, length and crack growth rate. The failure probabilities of each defect and the whole pipeline system can be obtained during simulation. Different inspection and repair criteria are available in the Monte Carlo simulation whereby an optimal maintenance strategy can be obtained by comparing different combinations of inspection and repair procedures. The simulation provides not only data on the probability of failure but also the predicted number of repairs required over the pipeline life thus providing data suitable for economic models of the pipeline management. This tool can be also used to satisfy certain target reliability requirement. An example is presented comparing a natural gas pipeline with a pipeline containing hydrogen.

Nomenclature

$f_{x_N}(x_N)$	distribution function of variables	c	half crack length
a	crack depth	t	wall thickness
$g(x)$	failure domain	Φ	standard normal distribution function
x_i	stochastically independent variable	K_r	ratio of applied elastic K to K_{IC}
L_r	ratio of applied load to yield load	ΔK_{th}	threshold stress intensity factor value
ρ	plastic correction factor	$L_{r\max}$	permitted limit of L_r
σ_Y	yield strength of material	σ_U	ultimate tensile strength of material
K_{IC}	Toughness of material	σ_{ref}	reference stress
N	number of cycles	$P_{D/a}$	probability of detection
p_f	probability of failure of a single defect	q	total number of cracks
C_i	total cost of repair program	C_s	cost of repairing a single crack
N_A	average number of cracks repaired	C_{pf}	probable cost of have a failure
$P_{f\text{total}}$	total probability of failure	C_f	cost of having a major failure
β	reliability index		

1. INTRODUCTION

Failure of a structural member such as a pipeline may occur when a crack propagates in an unstable manner to cause leak or explosion of the pipeline. Fracture mechanics combined with a probabilistic approach has been utilized in many fields of analysis involving important structural components such as pressure vessels and nuclear piping. Based on probabilistic fracture mechanics, statistical methods are applied in order to assess the reliability of pipeline containing crack-like defects [1], in other words, to provide a single number which represents the probability that a pipeline could fail. The aim of the NATURALHY project is to investigate the possibility of using the existing natural gas pipelines to deliver hydrogen or mixed natural-hydrogen gas. As zero tolerance to hydrogen leakage is widely accepted in the pipeline industry the concept of 'failure' of a pipeline includes both gas leakage and pipeline breakage.

Although in general the safety of pipelines is threatened by corrosion and crack like defects this paper concentrates on crack like defects as data suggests that only crack like defects are affected by the presence of hydrogen. Under the "slow" fatigue cycles hydrogen can affect the fracture toughness and the rate of growth of cracks.

2.0 THEORY

2.1 Fundamentals of reliability analysis

According to Probabilistic Fracture Mechanics (PFM) if one and only one crack exists in a pipeline, the failure probability is given by:

$$P_f = \int_{g(x_1 \dots x_N) \leq 0} f_{x_1}(x_1) \dots f_{x_N}(x_N) d(x_1) \dots d(x_N) \quad (1)$$

where $x_1 \dots x_N$ are random variables such as crack sizes, yield strength, crack growth parameters and applied stresses. As will be discussed in chapter 3, only semi-elliptical surface cracks will be considered as crack models with the crack depth a and crack length $2c$. The geometry of the model is shown in Fig. 1. $f_{x_N}(x_N)$ denotes the probability density function of the input variable x_N . The integration will be performed over the failure domain where $g(x_1 \dots x_N) \leq 0$.

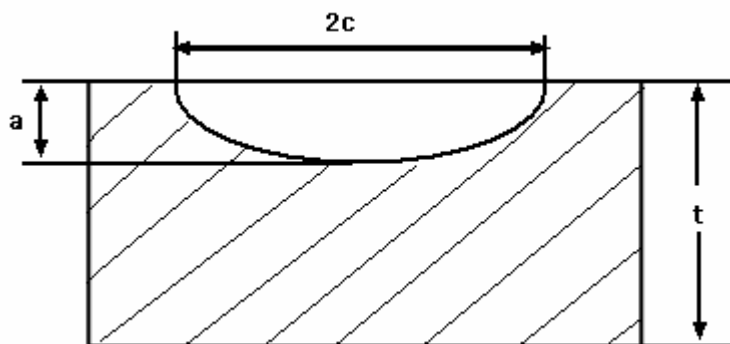


Figure 1. Geometry of the Semi-elliptical surface crack model used

For engineering applications a reliability index β is required to define the amount of safety of the structure, which is given by [2]:

$$P_f = \Phi(-\beta) \quad (2)$$

where Φ is the standard cumulative normal distribution function .

2.2 Failure assessment procedure

In the current reliability analysis a Failure Assessment Diagram (FAD) approach is adopted, which is shown in Fig 2. The g-function aforementioned is based on the BS7910 level 2 Failure Assessment Curve (FAC).

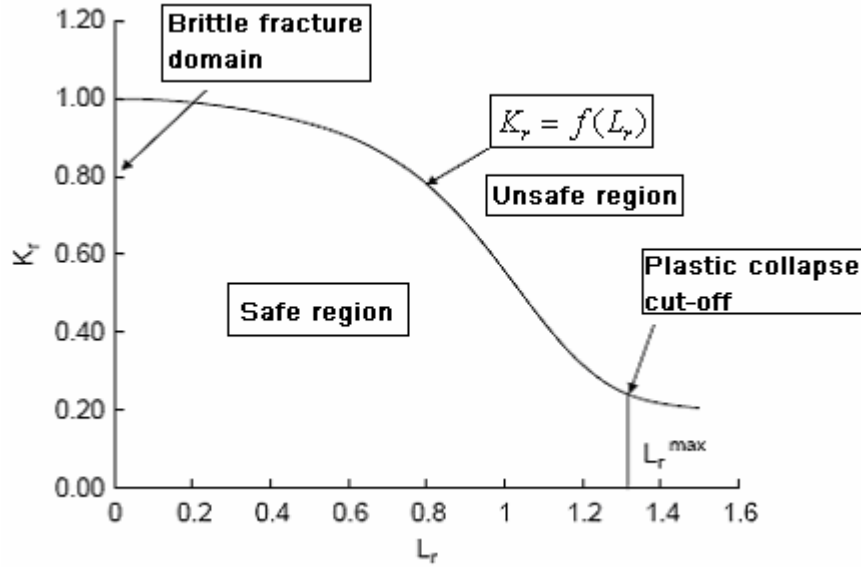


Figure 2. The FAC curve used in the calculation

The FAC is defined as follows:

$$\begin{cases} \text{for } L_r \leq L_{r \max} & K_r = (1 - 0.14L_r^2) \{0.3 + 0.7 \exp(-0.65L_r^6)\} \\ \text{for } L_r > L_{r \max} & K_r = 0 \end{cases} \quad (3)$$

The failure criterion includes both brittle fracture and plastic collapse. K_r measures the proximity to brittle fracture and L_r represents the likelihood of plastic collapse. For BS7910 level 2A FAD, they are given by:

$$\begin{cases} K_r = \frac{K_p + K_s}{K_{IC}} + \rho \\ L_r = \frac{\sigma_{ref}}{\sigma_Y} \end{cases} \quad (4)$$

ρ is a parameter that takes plastic interaction between primary and secondary stress into consideration. For materials that exhibit a yield discontinuity (referred to as Lüders plateau) L_r is restricted to 1.0 [3]. Otherwise it is calculated through:

$$L_{r\max} = \frac{\sigma_Y + \sigma_u}{2\sigma} \quad (5)$$

Since the cumulative probability of failure over a given timeframe is required, crack propagation due to cyclic loading must be included. The PARIS law with a threshold ΔK_{th} is selected to calculate the crack length and depth with regard to the corresponding number of cycles.

$$\frac{da}{dn} = \begin{cases} 0 & \text{for } \Delta K < \Delta K_{th} \\ C\Delta K^m & \text{for } \Delta K \geq \Delta K_{th} \end{cases} \quad (6)$$

The actual calculation in PipeSafety is performed by estimating the amount of crack growth during a loading cycle.

$$\begin{aligned} \Delta a &= C(\Delta K_a)^m \\ a_{n+1} &= a_n + \Delta a \end{aligned} \quad (7)$$

where a_n corresponds to the crack depth after n load cycles. An equivalent equation applies for the second axis of the semi-ellipse. The initial crack depth and length are modelled as variables and if necessary the fatigue property parameters can be also modelled as random variables based on certain distributions. As crack propagation could lead to fracture or leakage of the pipeline after a certain period of time, P_f is a function of load cycle n .

$$P_f = P(n) \quad (8)$$

P_f denotes the cumulative probability which monotonically increases with time or load cycles. The inclusion of inspection and repair program can slow down this process so as to meet certain target reliability targets.

2.3 Inclusion of inspection and repair program

As part of the normal operation and maintenance of pipelines, inspections are performed using intelligent “pigs” to detect defects in the pipeline. During inspections not all defects are identified due to the sensitivity of the tool. The process of inspection and repair of a pipeline at a given interval will change the distribution of crack depth and length because some of the detected cracks will be repaired. The exact distribution will depend upon the repair strategy adopted, the frequency of inspection and the sensitivity of the inspection tool. These remaining cracks will not lead to failure but those missed by the inspection tool might cause gas leakage or rupture of the pipeline. The maintenance event tree is displayed in Fig. 3.

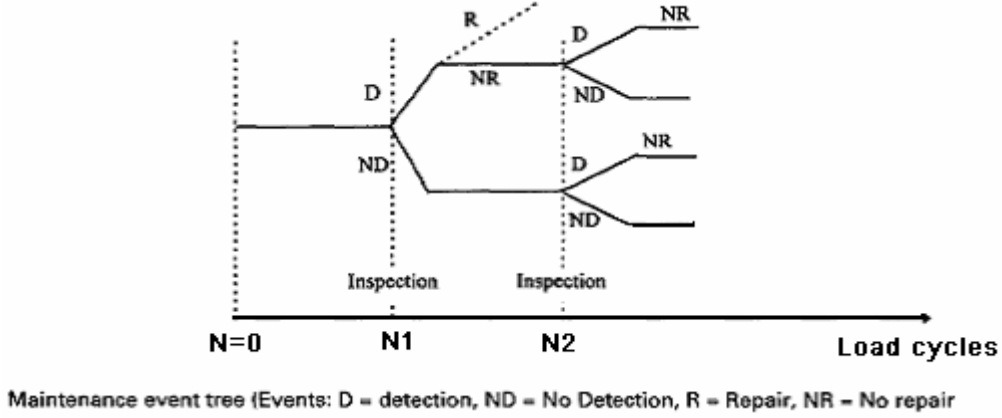


Figure 3. Maintenance event tree (adapted from [4])

So far the Probability of Detection (POD) has not been defined. The POD is usually an increasing function of defect depth and defined as an exponential function [4]:

$$P_{D/a} = 1 - e^{-\lambda a} \quad (9)$$

$P_{D/a}$ can be expressed as the cumulative distribution function for the detectable depth of the inspection tool. Hence, the detectable depth of the inspection tool follows the exponential distribution function and both the average detectable size and the standard deviation equal $1/a$. If inspection and repair program is introduced, the calculation of P_f is slightly more complex and the calculation is based on the intervals of the inspection and repair program [4]. If the pipeline is assumed to be running safely at $n = 0$ the cumulative POF before the first inspection is obtained as:

$$P_f(n) = P[S(0) \cap F(N)] / P[S(0)] \quad (0 < n < N_1) \quad (10)$$

and the POF between the first inspection and the second inspection is given by:

$$P_f(n) = P_f(N) + P_{f_1}(N) + P_{f_2}(N) \quad (N_1 < n < N_2) \quad (11)$$

$$P_{f_1}(n) = P[S(0) \cap S(N_1) \cap ND(N_1) \cap F(N_1)] / P[S(0)] \quad (12)$$

$$P_{f_2}(n) = P[S(0) \cap S(N_1) \cap D(N_1) \cap NR(N_1) \cap F(N_1)] / P[S(0)] \quad (13)$$

Where $S(n)$ is an event representing a crack that survives between 0 and n cycles. Similarly, $ND(n)$ refers to non-detection event; $D(n)$ means detection event; $NR(n)$ is non-repair event and $F(n)$ refers to an event where a crack lies in the un-safe area. As can be seen from the equations above, when the cycle number is between 0 and N_1 the calculation of POF is straightforward. However, after the first inspection and repair program, the calculation of POF is composed of two parts. The first component $P_{f_1}(n)$ corresponds to the cracks that are un-detected and will lead to failure. $P_{f_2}(n)$ corresponds to the detected but un-repaired cracks that eventually result in failure. If more than one inspection program exists, similar expressions can be deduced. These expressions are

mathematical representation of the maintenance event tree that has been shown in Fig. 3. In addition to the probability of failure, the probability of repairing a single crack is obtained as follows:

$$P(R | n = N_1) = P[S(0) \cap S(N_1) \cap D(N_1) \cap R(N_1)] / P[S(0)] \quad (14)$$

This expression means the repaired cracks are those that survived the first inspection and are detected and repaired by the inspection tool.

There are three options for repair criteria: a) any cracks detected are repaired; b) only the cracks that are larger than a certain size are repaired; c) the cracks that will lead to failure after a pre-determined period of time will be repaired. This time period is usually defined by the pipeline operator.

3.0 MONTE CARLO SIMULATION

3.1 Monte Carlo simulation procedure

Solution to Eq. (1) can be solved by Monte Carlo simulation. By generating a large number M of independent repetitions, the probability of failure can therefore be estimated as the quotient of the failure counts to the number of simulations performed, which is given as follows:

$$P_f = \frac{M_f}{M} \quad (15)$$

The above equation is valid when the pipeline only contains one crack. When there is more than one crack in the system, say q stochastically independent cracks, the total probability of failure is the probability that at least one crack will lead to failure, which is obtained by [2,4]:

$$P_{f_{total}} = 1 - (1 - P_f)^q \quad (16)$$

The scheme of the Monte Carlo simulation is presented in Fig. 4. The first step is to generate random numbers based on the selected probability distribution functions. These variables include the crack depth, length, material properties, geometry of the pipe, etc. The simulation follows the same logic as is illustrated in the previous chapters.

3.2 Random variables and sampling method

The defect sizes given by non-destructive testing can follow a normal, lognormal or exponential distribution [5]. In addition, the distributions of other parameters have been investigated by some authors [6-8].

Once a random number between 0 and 1 has been generated, it can be used to generate required random variables with a given probability distribution function. The inverse transform method [9] is a common method to achieve this, which is based on the observation that continuous cumulative distribution functions (cdf) range uniformly over the interval (0, 1). If u is a uniform random number on (0, 1), then a random number x from a continuous distribution with selected cdf F can be obtained using:

$$x = F_x^{-1}(u) \quad (16)$$

However, for normal distribution the inverse of the cumulative distribution function cannot be found analytically. Hence, other methods such as the Box-Müller method or the envelop-rejection method is used in the simulation [9].

There are two sampling methods for Monte Carlo simulation:

- a) Direct Monte Carlo simulation
- b) Monte Carlo simulation with variance reduction: stratified sampling or importance sampling

The software developed for the current project employs both direct Monte-Carlo method and Monte-Carlo method with stratified sampling. In this paper the direct Monte Carlo simulation has been explained and the detailed information about the variance reduction techniques can be found in literature [8].

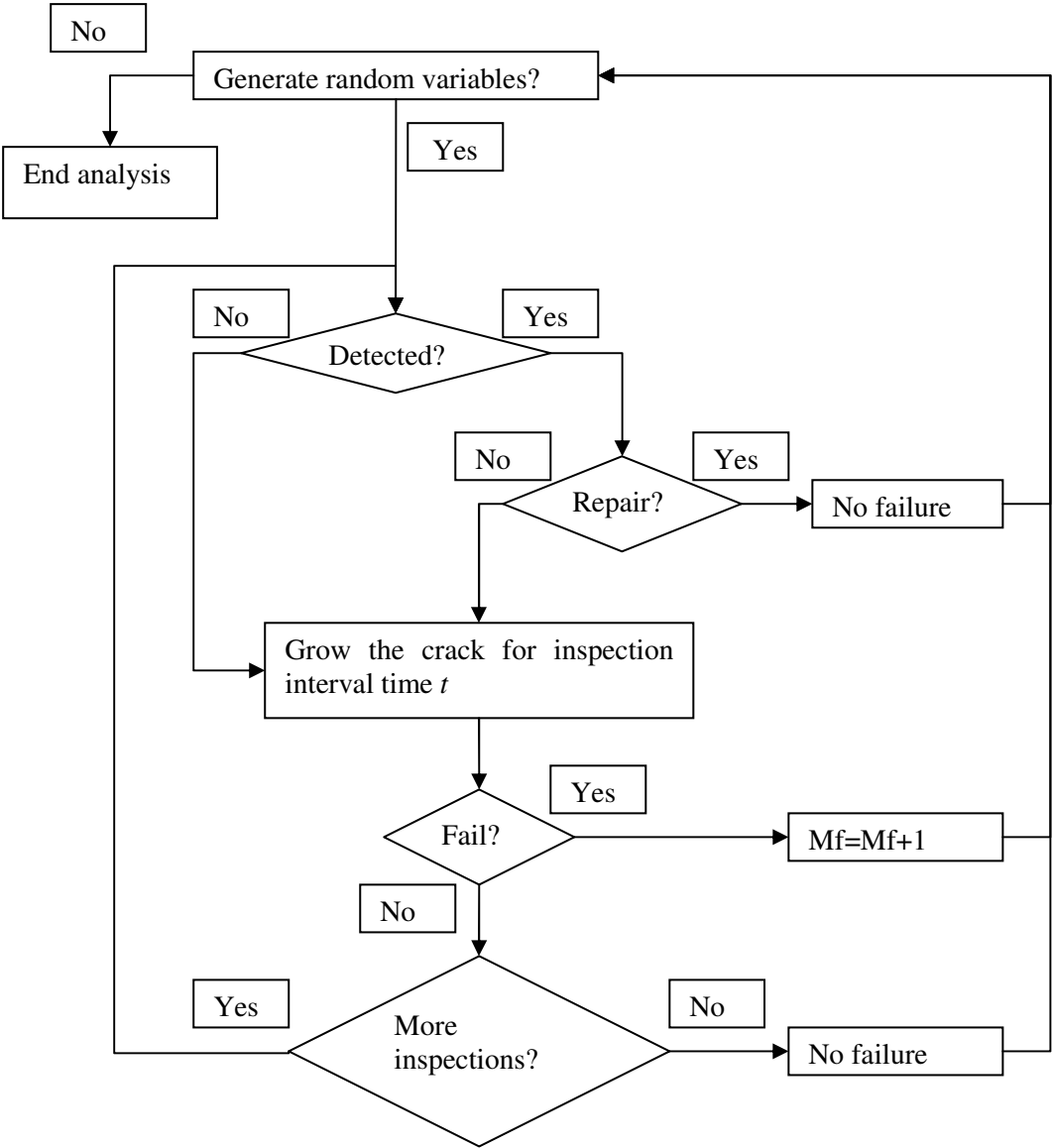


Figure 4. Flow chart of POF Monte Carlo analysis

4. DEVELOPMENT OF PFM TOOL-PIPESAFETY

Fig. 5 shows the first page of the POF calculation software PipeSafety. The software is composed of six modules, which includes geometry definition, load definition, material property definition, inspection tool definition, repair criteria definition and finally the settings of calculation.

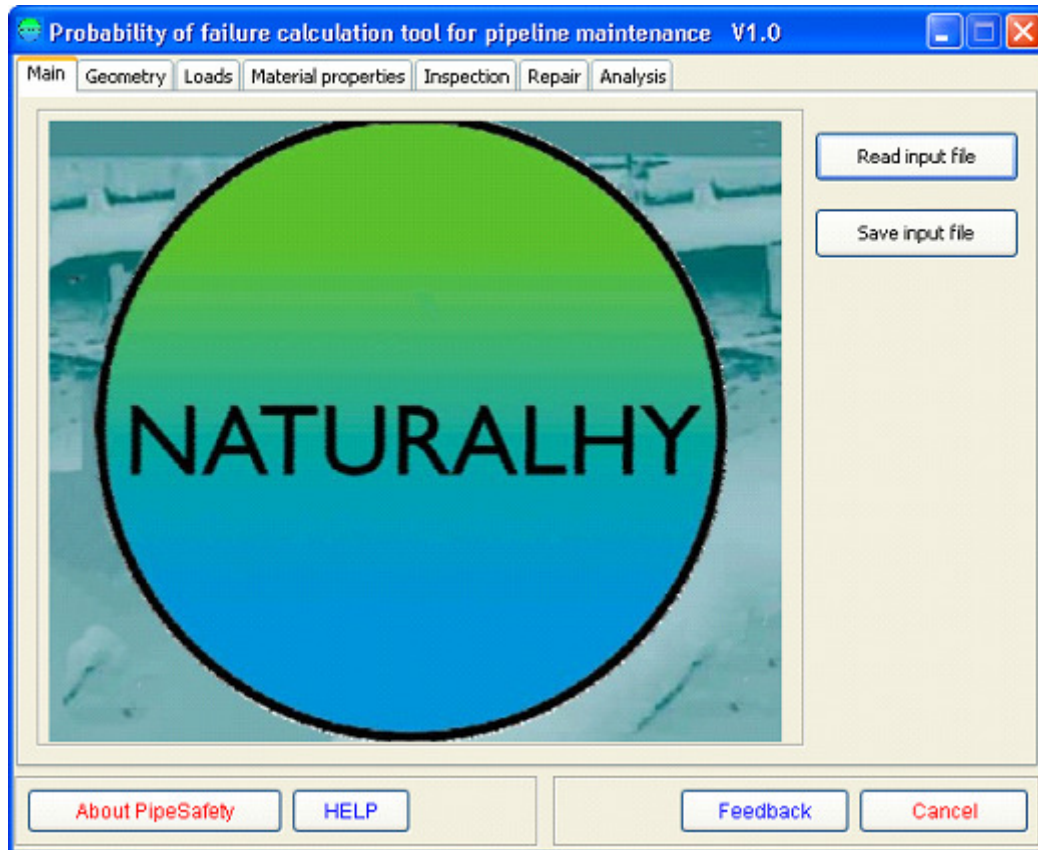


Figure 5. Main page of PipeSafety software

5.0 SAMPLE PROBLEMS

5.1 Data preparation

The following examples will illustrate the POF calculation and maintenance procedure of an X52 pipeline based on the input data listed in Table 1. The aim is to investigate the impact of the introduction of hydrogen on the total probability of failure within a given timeframe. We assume the pipeline is pre-inspected and the total number of cracks per km in base material and weld is 10cracks/km respectively [11]. Also all cracks are assumed to be longitudinally oriented.

Table 1. Input parameters for POF analysis of X52 steel in natural gas and hydrogen pipeline

No.	Parameter	Average	Standard deviation	Distribution type
1	Pipe diameter (mm)	600	0	Fixed
2	Wall thickness (mm)	10	0	Fixed
3	Initial crack depth (mm)	2.85	0.9	Log-normal

No.	Parameter	Average	Standard deviation	Distribution type
4	Initial crack length (mm)	150	25	Log-normal
5	Pressure (MPa)	6.06	0	Fixed
6	Residual stress(MPa)	Base metal or weld with relaxation	0	Fixed
7	Fracture toughness (MPa*mm ^{1/2})	Assumed 4743.4 for N ₂ and 1581.1 for H ₂ [10]	0	Fixed
8	Yield strength (MPa)	410	20	Normal
9	Tensile strength (MPa)	528	25	Normal
10	Threshold toughness (MPa*mm ^{1/2})	632.45	0	Fixed
11	Fatigue parameter c (Natural gas)	5.2×10 ⁻¹³ [10]	0	fixed
12	Fatigue parameter m (Natural gas)	3[10]	0	fixed
13	Fatigue parameter c (Hydrogen)	2.4×10 ⁻¹⁴ [10]	0	fixed
14	Fatigue parameter m (Hydrogen)	3.8[10]	0	fixed
15	Inspection interval	Pre-inspected and will be inspected at every 10 years	0	fixed
15	Inspection tool precision	95% probability of detection 4% wall thickness	0	fixed
16	Repair criterion	Repaired if the crack will lead to failure in 12 years	0	fixed
17	Pressure drop ratio	0.35	0	fixed
18	Service life (years)	40	0	fixed
19	No. of cycles per year	365	0	fixed

5.2 Probabilistic fracture failure analysis results

Using PipeSafety software, the cumulative probability of failure can be obtained as shown in Table 2. As can be seen from the results, introduction of 100% hydrogen will significantly affect the reliability of the pipeline and therefore extra care has to be taken when dealing with hydrogen pipelines. The average number of cracks repaired is also computed and the total cost of inspection and repair program can be calculated by:

$$C_t = N_A \times C_s \quad (16)$$

where C_t is total cost; N_A is the average number of cracks repaired and C_s is the cost of repairing a single defect. Similarly the probable cost of failure is:

$$C_{pf} = P_{f\text{total}} \times C_f \quad (17)$$

where C_{pf} is the probable cost of failure and $P_{f\text{total}}$ is the total probability of failure and C_f is the cost of a major failure.

Table 2. Monte Carlo simulation results of the X52 pipeline in different gas media

	Cracks in natural gas	Cracks in Hydrogen	Cracks in weld and natural gas	Cracks in weld and hydrogen
$P_f(t = 40 \text{ years})$	3×10^{-5}	6.43×10^{-4}	6.73×10^{-4}	1.4025×10^{-1}
Average number of cracks repaired	3.9022	9.9736	3.8958	8.5941
$P_{f\text{total}}$	3.0×10^{-4}	6.411×10^{-3}	6.71×10^{-3}	7.793×10^{-1}

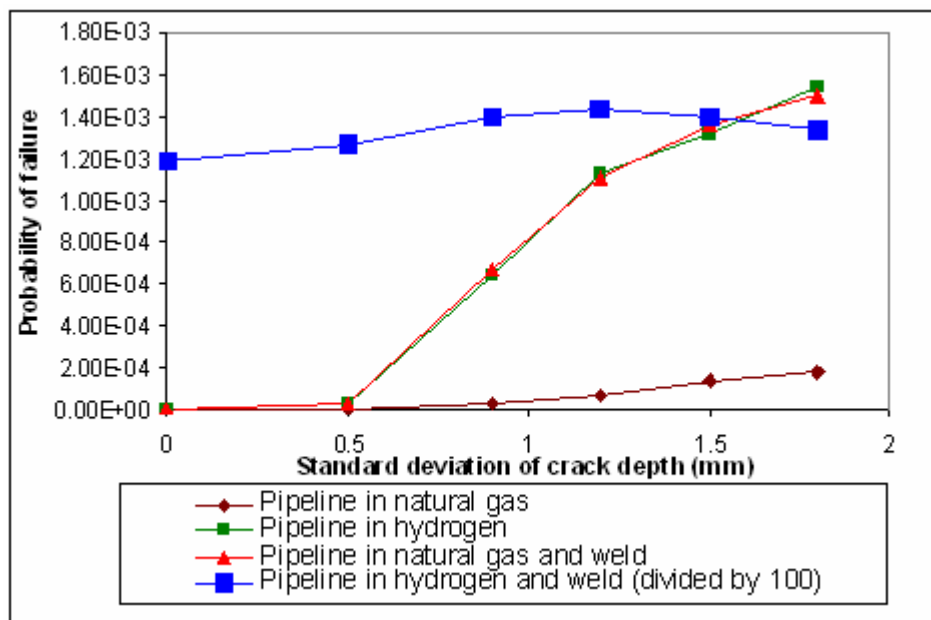


Figure 6. POF vs. standard deviation ("divided by 100" means POF has been scaled down by 100)

It is well known that the POF is heavily dependent on the distribution of the defects in the pipeline and in particular the crack depth [12]. Fig. 6 shows how the POF changes as the standard deviation of crack depth increases. Fortunately many pipelines have been operating safely carrying Natural gas for many years which enables the Standard Deviation to be estimated from current safety data. Therefore in Fig. 6 it is shown that if the current POF of a gas pipeline is 10^{-5} then for the same pipeline carrying 100% hydrogen the POF will increase to 10^{-4} assuming it is operated in the same manner. If pipelines carrying natural gas-hydrogen mixture are used we expect the POF could be lower than that of the pure hydrogen pipelines. However the fatigue properties of X52 in natural gas-hydrogen mixture are not clear now and massive experiments are being performed. Once sufficient data are obtained POF of different types of pipeline can be predicted using the same approach as proposed.

6. CONCLUSIONS

A methodology based on BS7910 has been presented for assessment of the safety of pipelines carrying hydrogen or natural gas. The methodology is based on Monte-Carlo simulation which includes the assessment of crack like defects and the inspection and repair strategy.

The existence of hydrogen in a pipeline significantly affects the safety of the pipeline and the probability of failure for all the cases considered. The reason for this is the change in the fatigue and fracture properties of the material induced by hydrogen. Another important element of the POF calculation is the assumed distribution of crack like defects present in the pipeline at the start of its operation with hydrogen. For example a new pipeline will have a smaller number of initial defects than an older one. As can be seen from the results of the examples, different input data such as mean value or standard deviation of the crack sizes can lead to very different POF results. Other service conditions such as pressure drop ratio, number of cycles and the type of defects (e.g. base metal defects, weld defects, crack like defects associated with third party damage) have to be considered. Hence, when calculating POF much importance should be attached to the way how this data is collected and used. There are several assumptions made in this paper that need to be noted:

a) Crack size distribution

In this report, only lognormal function is adopted to represent the actual distribution of the defects in pipeline. However, there are other functions such as Weibull and exponential distributions, which can also be used to fit the data. In addition, the crack length and depth should be examined very carefully since the results could become rather different for any slight change of the input data.

b) Number of cracks in welds

Currently it is impossible to know the exact number of cracks in the pipeline so sensible assumptions have to be made. In this report, the assumed number of defects is based on TNO's report [11].

c) Detection probability

Detection probability is essentially related to the distribution of the crack depth. The larger the crack depth is, the higher possibility that a crack can be detected by the inspection tool is. In the current analysis it was assumed the minimum detectable depth is 0 mm but this might not reflect the real precision of the inspection tool. A shifted POD curve is used for more realistic situation where the minimum detectable depth is larger than 0 as shown on the right hand side of Fig. 7.

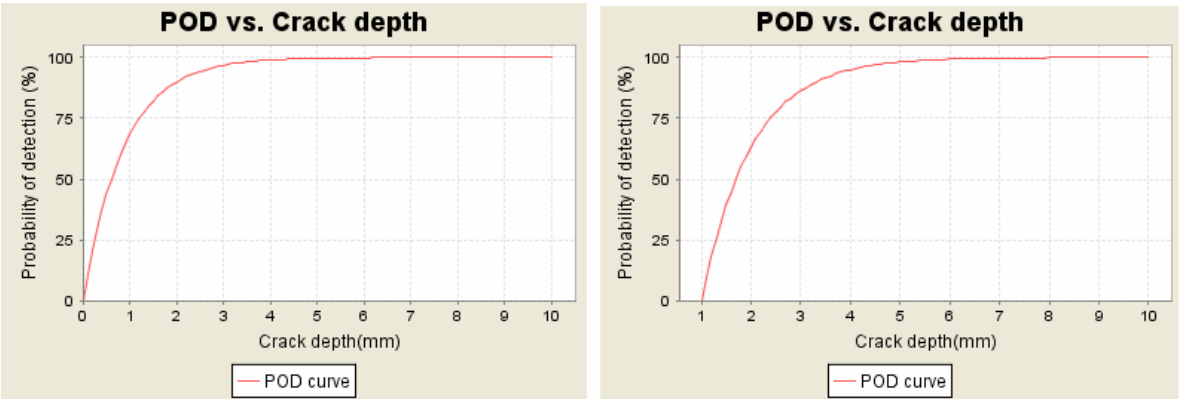


Figure 7. POD vs. crack depth

This paper presents a probabilistic approach to estimate the pipeline reliability incorporating inspection and repair program over the service life of the pipeline which contains crack-like defects. Monte Carlo simulation based software has been developed to calculate the POF and help engineers and decision makers of the pipeline operators to determine the optimal inspection and repair interval. The data presented show that the introduction of 100% hydrogen to an existing natural gas pipeline with crack-like defects will dramatically increase the POF of the pipeline system if the pipeline is continued to be inspected and repaired in the same way.

The current work is extending the calculations to natural gas and hydrogen mixtures.

ACKNOWLEDGEMENTS

The authors would like to thank the NATURALHY project partners for providing data and information and the European Union for kindly providing the financial support for this study.

REFERENCES

1. A.Bruckner and D.Munz, Determination of Crack Size Distributions from Incomplete Data Sets for the Calculation of Failure Probabilities. *Reliability Engineering*, 1985. 11: p. 191-202.
2. Thoft-Christensen, P. and M.J. Baker, *Structural Reliability Theory and Its Applications*. 1982: Springer-Verlag.
3. Guide to methods for assessing the acceptability of flaws in metallic structures (BS7910). 2005: British Standards Institution.
4. M.D.Pandey, Probabilistic Models for Condition Assessment of Oil and Gas Pipelines. *NDT&E International*, 1998. 31(5): p. 349-358.
5. Y.C.Lin and Y.J.Xie, Expert System for Integrity Assessment of Piping Containing Defects. *Expert Systems with Applications*, 2006. 30: p. 149-155.
6. G.Walz and H.Riesch-Oppermann, Probabilistic Fracture Mechanics Assessment of Flaws in Turbine Disks Including Quality Assurance Procedures. *Structural Safety*, 2006. 28: p. 273-288.
7. H.Adib, et al., Evaluation of the effect of corrosion defects on the structural integrity of X52 gas pipelines using the SINTAP procedure and notch theory. *Pressure Vessels and Piping*, 2007. 84: p. 123-131.
8. W.Provan, J., ed. *Probabilistic Fracture Mechanics and Reliability. Engineering Application of Fracture Mechanics*, ed. G.C. Sih. Vol. 6. 1987, Martinus Nijhoff Publishers.
9. J.S.Dagpunar, *Simulation and Monte Carlo*. 2007: John Wiley & Sons Ltd.
10. Krom, A., L. Zhang, and R. Adey, WP4 TASK B: Critical defect sensitivity studies. 2006, TNO Netherlands & CMI UK.
11. Wortel, H.v., Probability of Detection (PoD) and Probability of Failure (PoF) of flaws in the natural gas network (first draft). 2006, TNO.
12. A.Bruckner and D.Munz, The Effect of Curve Fitting on the Prediction of Failure Probabilities from the Scatter in Crack Geometry and Fracture Toughness. *Reliability Engineering*, 1982. 5: p. 139-156.