PREDICTION OF THIRD PARTY DAMAGE FAILURE FREQUENCY FOR PIPELINES TRANSPORTING MIXTURES OF NATURAL GAS AND HYDROGEN

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ABSTRACT

As Europe is gradually moving towards a hydrogen based society it has been acknowledged that adding certain amount of hydrogen, as a clean energy carrier, to the existing natural gas pipeline will help reduce the CO_2 emissions which contribute to the greenhouse effect. On the other hand, hydrogen has been demonstrated to be able to change the behaviour of the pipeline steel such as lower toughness and faster crack growth due to hydrogen embrittlement. Therefore, it is necessary that the risks associated with the failure of the pipeline carrying mixtures of natural gas and hydrogen be assessed.

The study reported in this paper is part of European NATURALHY project, whose aim is to investigate the possibility of using the existing natural gas transmission pipelines to convey natural gas/hydrogen mixtures. According to the EGIG database, the most common cause of failure for the existing natural gas pipelines is third party damage, which mainly refers to a gouge, a dent/gouge combination of known geometry. Among third party damage failures, 90% are the result of immediate failure i.e. leakage or rupture of the pipeline and only 10% of them are the result of delayed failure. While its not expected that hydrogen will impact the immediate failure it could increase the vulnerability of the pipe to delayed failure through the initiation or activation of crack like defects.

This paper will present a methodology to predict the probability of increased failures and describe a software tool that has been developed to perform the calculations.

Nomenclature

P_m	primary stress	P_b	half crack length
H	dent depth	D	nominal pipe diameter
σ_H	nominal hoop stress	t	pipeline wall thickness
M	bending moment	ΔK_{th}	threshold stress intensity factor range
m	fatigue growth parameter	C	fatigue growth parameter
a	crack depth	$2c$	crack length
W	pipe section length	K	mode 1 stress intensity factor
K_r	ratio of applied elastic K to K_{IC}	L_r	ratio of applied load to yield load
K_{IC}	toughness of material	ρ	plastic correction factor
K_P	primary stress intensity factor	K_S	secondary stress intensity factor
$L_{r\max}$	permitted limit of L_r	σ_{ref}	reference stress
σ_Y	yield strength of material	σ_U	ultimate tensile strength of material
P_f	probability of failure	K_f	failure frequency

1.0 INTRODUCTION

Among all failure modes for gas pipelines third party damage poses the greatest threat to the safety of the pipeline network because it accounts for more than 50% of the total incidents according to a recent survey [1]. Some of the failures do not happen immediately after the pipeline is damaged but occur years after the strike. The aim of the current study is to investigate if adding hydrogen to the existing natural gas pipeline network will increase the risk of delayed failure.

Europe is investigating the adding of Hydrogen to the gas transmission system as it is believed to be one of the most promising energy carriers in the 21st century. However, the transition from pure natural gas pipelines to pipelines carrying natural gas/hydrogen mixtures entails extra risk to the integrity of the pipeline as hydrogen has been shown to reduce the toughness of the pipeline and to accelerate crack growth. The NATURALHY project has concluded that hydrogen molecules within the pipeline presents no hazard to the pipeline steel unless the inner thin oxide layer on the pipeline steel is disturbed and a crack-like defect exists which can cause disassociation of the hydrogen molecules and allow hydrogen to permeate into the pipe body, thereby reducing the material toughness. Crack like defects may be present on the inner wall of the pipe as a result of manufacturing defects, or as a result of some kind of third party damage. In the case of third party damage a crack may be initiated on the inner wall of the pipe due to the incident. Alternatively the damage may activate an existing dormant crack (i.e. a crack which is not growing or growing so slowly that it is not significant). The second case would be very unlikely but it is theoretically possible.

The following sections propose a methodology to predict the impact of hydrogen on the delayed failure probability associated with the dent where a crack has been initiated/activated due to third party damage.

2.0 ESTIMATING THE MAXIMUM PERMISSIBLE CRACK DEPTH

2.1 Set-up of the dent-crack model

The dent in a pipeline is a complex structural problem as the stress distribution at the root of the dent is heavily influenced by the depth of the dent, the included angle of the dent, the length of the dent and the location of the dent. A detailed description of the elastic analysis of a dent on a pipe can be found in references [2, 3]. To solve this complex problem a simplified model has been adopted. The loading applied to the crack embedded at the bottom of the dent can be described by following relationships [4].

$$P_m = \sigma_H \left(1 - 1.8H / D\right) \tag{1}$$

$$M = 0.85\sigma_H tH \tag{2}$$

$$P_b = 6M / t^2 \tag{3}$$

The only difference between a surface crack in an undamaged pipe and in a dented pipeline is that there are additional stresses caused by bending around the dent but the membrane stress is lower. If the bending stress is not relaxed when the dent is constrained by a rock, re-rounding is not possible. The dent depth follows the Weibull distribution with α of 0.69 and β of 6.202 mm according to UKOPA fault database [5]. For the current study, the dent depth is chosen to be **6mm** as this represents a typical dent depth in the pipeline (see Fig. 1).

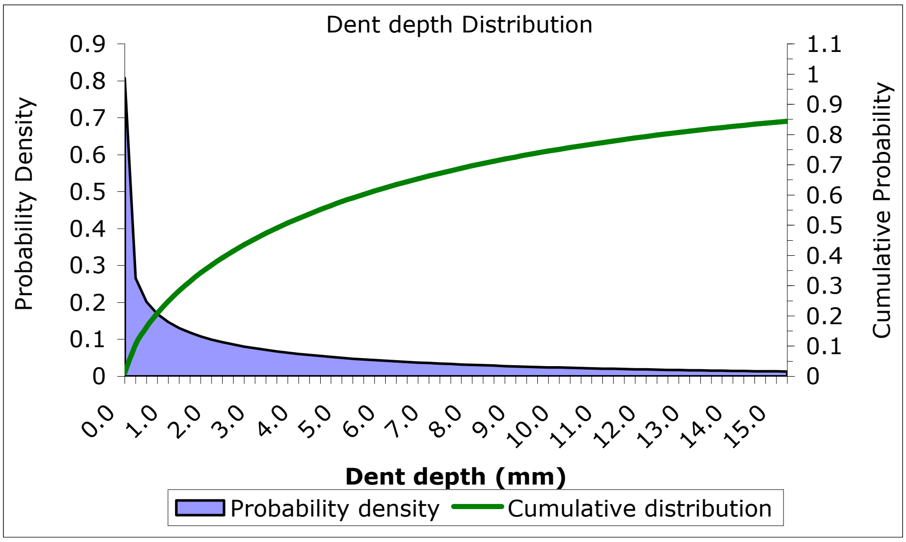

Figure 1. Dent depth distribution

The transmission gas pipeline considered is made of X70 of wall thickness 12.9 mm and diameter 900 mm. This represents a typical modern pipeline made after 1975. The geometry of the pipe, the dent and the crack are shown in Fig 2. The operating pressure of the pipeline is assumed to be 60 bar. The material properties for X70 pipeline in different natural gas/hydrogen mixtures are summarised in Table 1. The data represents a typical X70 pipeline. It has to be noted that the pipelines manufactured before 1975 might have significantly lower toughness values and more vulnerable to crack propagation. In this case the figures shown in the table are not applicable and additional experimental results are required to describe the material properties.

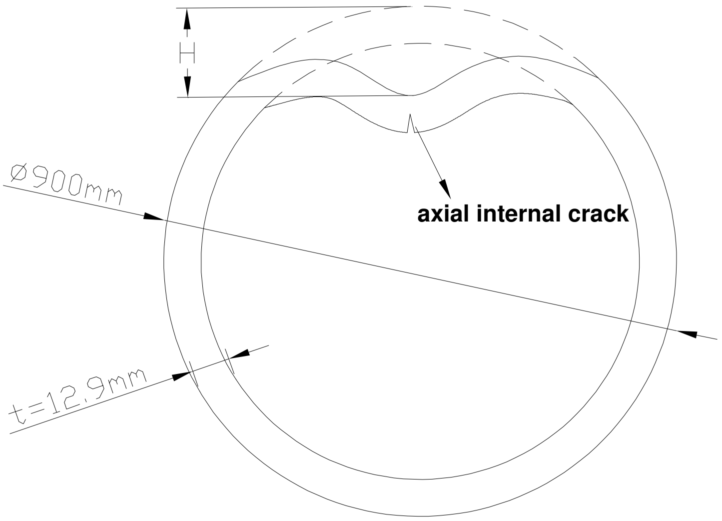

Figure 2. Geometry of the pipeline with a crack embedded in a dent

Table 1. Material properties of X70 (internal pressure = 60 bar)

Gas contents	Yield strength (MPa)	Ultimate tensile strength (MPa)	Toughness for pipelines (MPa√m)
100% NG	482.6	565	200
50% NG+50% H2	482.6	565	150
100% H2	482.6	565	100

The problem of a crack embedded in the dent can be solved using a flat plate model as shown in Fig. 3. W is the pipe section which is long enough to accommodate the crack defect. The crack is axially oriented so that the hoop stress applied to the crack surface is the maximum. The pressure swing ratio used here is 0.35, which is a fairly large number for an average gas pipeline network. However, this number is used during the pipeline design process, so it is also used for fatigue calculation. Here the failure of the pipeline refers to general failure, i.e. either leakage or rupture of the pipeline.

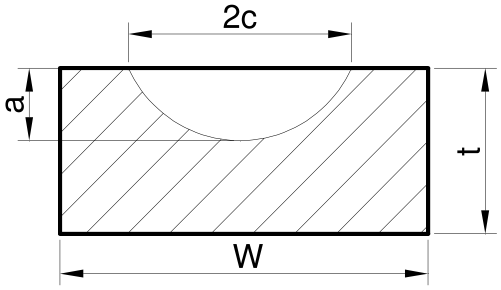

Figure 3. Geometry of the Semi-elliptical surface crack model

2.2 Calculation of the maximum permissible crack depth

For the current study BS7910 level 2 Failure Assessment Diagram (FAD) is adopted. As can be seen from Fig 4 if a crack is initiated in the safe region it does not lead to failure immediately, but once it grows outside the safety boundary, which is depicted on the graph, the pipeline becomes unstable and leakage/rupture can occur. In this section a series of sensitivity tests are performed, for which the maximum crack depth that will not cause immediate failure is calculated.

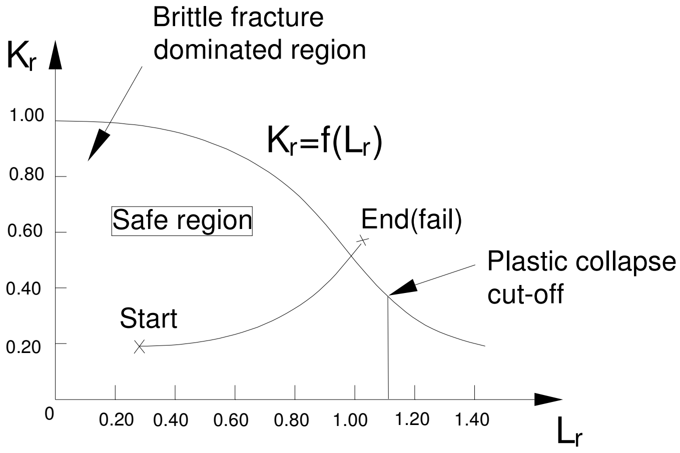

Figure 4. BS7910 Failure Assessment Diagram (FAD)

According to BS7910 the failure boundary is defined as follows:

$$\begin{cases} \text{for } L_r \le L_{r\max} & K_r = (1-0.14L_r^2)\left\{0.3+0.7\exp(-0.65L_r^6)\right\} \\ \text{for } L_r > L_{r\max} & K_r = 0 \end{cases} \tag{4}$$

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:

$$\begin{cases} K_r = \dfrac{K_P + K_S}{K_{IC}} + \rho \\ L_r = \dfrac{\sigma_{ref}}{\sigma_Y} \end{cases} \tag{5}$$

ρ is a parameter that takes plastic interaction between primary and secondary stress into consideration. For materials, especially low strength materials that exhibit a yield discontinuity (Lüders plateau) L_r is restricted to 1.0 [12]. Otherwise it is calculated through:

$$L_{r\max} = \frac{\sigma_Y + \sigma_u}{2\sigma_Y} \tag{6}$$

The above equation is used for the analysis of the current study as the Lüders plateau is not visible for high strength steel such as X70. The results of the sensitivity tests are displayed in Fig. 5. It can be seen that for modern pipelines with a relatively high toughness hydrogen does not have much impact on the integrity of the pipeline when the cracks have just formed in the dent. For these pipelines the failure mechanism is plastic collapse rather than brittle fracture. It is also discovered that the critical depth (i.e. the crack depth which will lead to immediate failure) declines as crack length increases and the critical crack depth levels off as the crack length reaches about 130 mm. However, for old pipelines both brittle fracture and plastic collapse could be the failure mechanism.

Although preliminary sensitivity tests suggest modern pipelines with a high toughness are less susceptible to hydrogen it will be shown that once the crack starts growing in the dent the associated risks will increase as time elapses. Replacing part of natural gas with hydrogen does make pipelines vulnerable and the severity of the damage depends on the content of hydrogen.

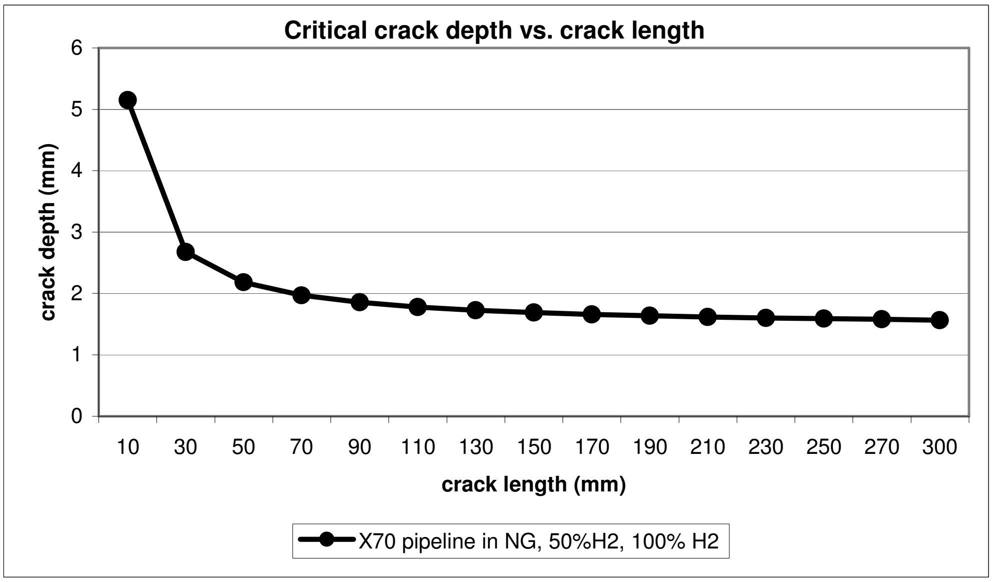

Figure 5. Critical crack depth vs. crack length for an X70 pipeline (60 bar, dent depth=6mm)

3.0 ESTIMATION OF THE DELAYED FAILURE PROBABILITY OF DENTED PIPELINES

3.1 Crack growth in the dent

Among all third party damage related failures, 90% of them are immediate failures and the rest are delayed failures [7]. Delayed failures refer to those that do not occur when the pipeline is damaged but occur years after it was damaged. From the sensitivity test results as seen in the previous section it can be concluded that any cracks present in the pipeline must be smaller than those shown in Fig. 5 as any larger cracks would have led to immediate failure.

Since the cumulative probability of failure over a given timeframe is required, crack propagation due to cyclic loading must be included to estimate how the growth of cracks will impact the number of failures. 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.

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

The actual calculation is performed by estimating the amount of crack growth during a loading cycle and the detailed procedures can be found in authors' another paper [8]. According to Paris equation:

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

where a_n corresponds to the crack depth after n load cycles, C and m are fatigue growth parameters.

3.2 Procedures for estimating the failure probability

The failure probability can be calculated through Monte-Carlo simulation. By generating a large number N 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:

$$P_f = \frac{N_f}{N}$$

where N_f is the number of failures recorded. The whole process is shown in Fig. 6. The flow chart is simplified as the real simulation involves fatigue calculation, inspection and repair program. Relevant information can be found in reference [8]. Because crack propagation can lead to fracture or leakage of the pipeline after a certain period of time, P_f is a function of load cycle n.

$$P_f = P(n) \tag{8}$$

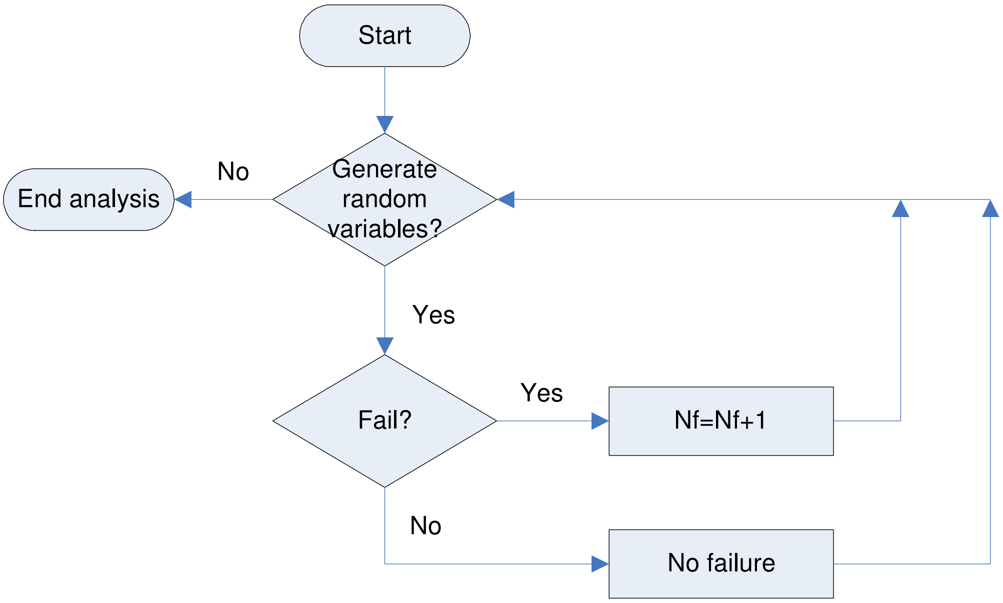

Figure 6. Flow chart of Monte-Carlo simulation

P_f denotes the cumulative probability which monotonically increases with load cycles. This value is only associated with the dent which has a crack at the bottom of it and the crack is very small which does not lead to failure at the beginning. As we do not know how many cracks are associated with dents, we therefore have assumed that all dents under consideration contain a surface crack.

If we assume that all dents have a depth of 6mm. The failure frequency of a pipeline arising from such defects in year 'u' can be approximated by:

$$k_f(u) = \sum_{i=0}^{u} \frac{P_f(i+1) - P_f(i)}{1 - P_f(i)} \times k \tag{9}$$

where k is the incident rate per km per year (kmy) and u for year. According to UKOPA database, the dent and gouge related incident rate is 8.49×10^{-4} per kmy, but the dent related incident rate is around 1.68×10^{-4} per kmy. Equation 9 implies that the defects which do not lead to failure in previous years may contribute to the failure frequency in the future.

3.3 Distributions of defect dimensions

The biggest difficulty in predicting the failure probability arises from the fact that information on the distribution of cracks imbedded in the dent is not available because currently inspection tools are not used to detect cracks in gas pipelines. Also there are many factors which influence the probability of failure based on the assumed incident scenario. For example if the POF of a single dent is considered the analysis must consider the severity of the dent, the probability that a crack is initiated on the inside wall of the dented pipe, the probability that there is a pre existing crack on the inside wall of the pipe near the dent and the frequency of such a dent causing incident occurring. In addition there is also the scenario regarding the introduction of hydrogen gas mixtures into the pipeline. For example has the pipeline been inspected and repaired? Was the dent pre-existing? Or did it occur after the introduction of the hydrogen gas mixture etc.

While calculation can be performed for the different scenarios the results will be very much dependent upon the defect distribution assumed in the pipeline. The following section attempts to simulate the POF for the case where the pipeline has been previously operating safely with natural gas and now is operating with a hydrogen gas mixture and the dent occurs and a crack is present on the inside wall either because it is initiated or as a consequence of the dent was pre existing in the pipe at that location.

Based on the sensitivity test results shown in section 2, it is possible to estimate the distribution of the length and depth of the crack imbedded in a dent which is 6mm deep. It is proposed that the following log-normal distributions for initial defect depth and length in dents are used to calculate the failure probability. The estimation is based on the findings of the sensitivity tests which show shorter cracks generally have larger critical depth up to a certain crack length where the critical depth stabilises. The log-normal cumulative curves, which give the probability of the occurrence of a specified size of damage or smaller, are plotted for crack depth and crack length for a long but shallow crack in Fig. 7 and Fig. 8. Fig. 9 and Fig. 10 are for short but deep cracks. Examining the curves it can be seen from Fig. 7 and Fig. 8 that they have been designed to have a very small number of defects with a depth greater than 1.5 mm which was the critical crack depth for a long crack in a dent in the pipeline. While there are still a small number of defects above the critical crack depth they are not significant as they only lead to a small increase in the POF in the early years.

Table 2. Distributions of crack depth and length

Variable	Type of distribution	Mean (mm)	Standard deviation (mm)
Depth (long cracks)	Log-normal	0.8	0.2
Length (long cracks)	Log-normal	15	5
Depth (short cracks)	Log-normal	2	0.3
Length (short cracks)	Log-normal	5	2

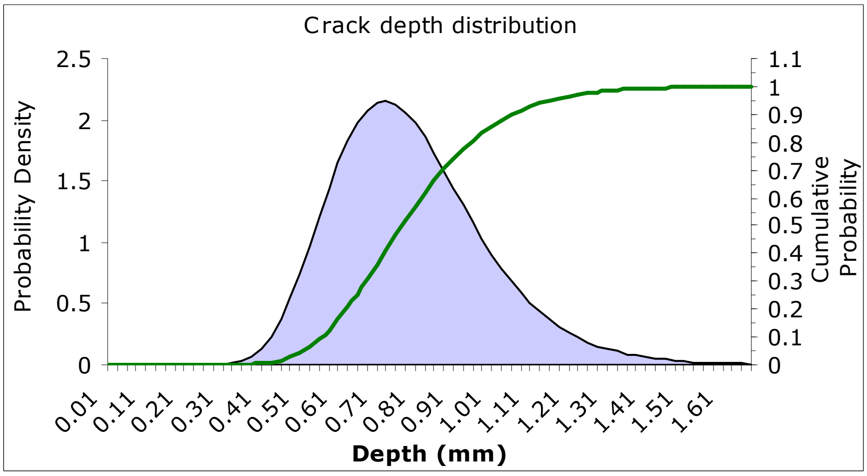

Figure 7. Crack depth distribution (long cracks)

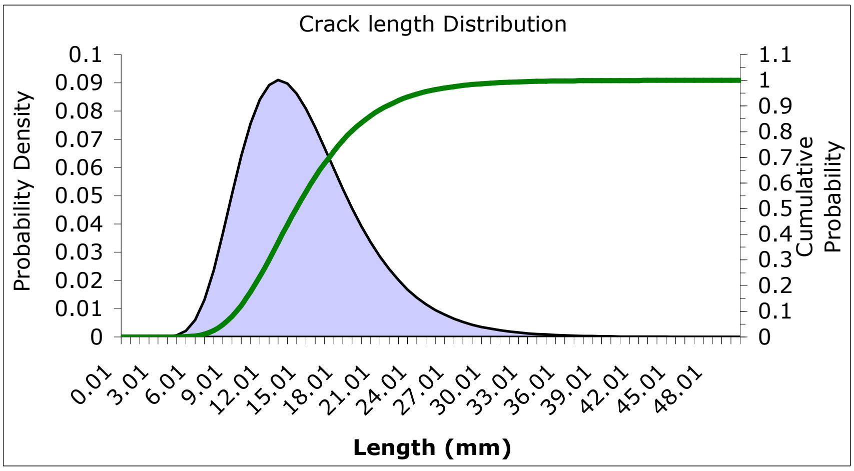

Figure 8. Crack length distribution (long cracks)

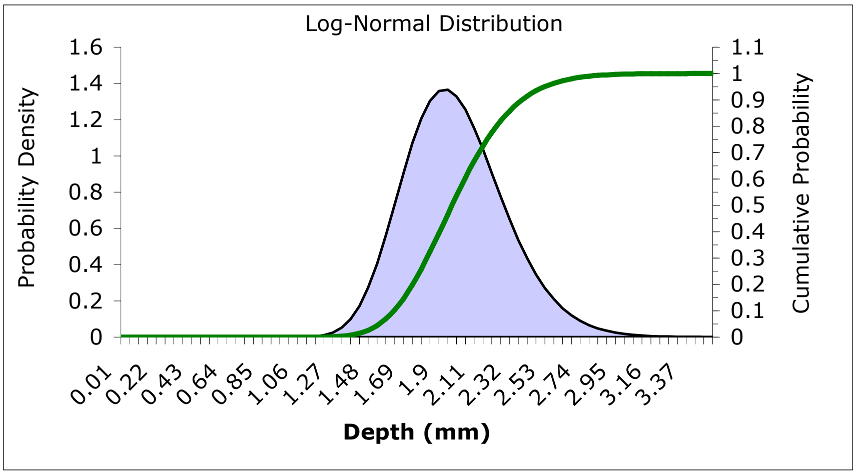

Figure 9. Crack depth distribution (short cracks)

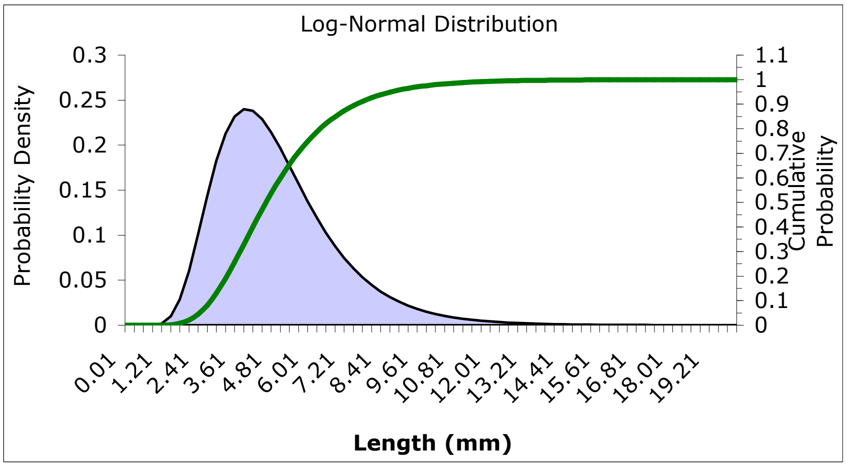

Figure 10. Crack length distribution (short cracks)

3.4 Comparing the delayed failure probability for natural gas pipelines and pipelines carrying natural gas/ hydrogen mixtures

Based on the assumed defect distributions and the dent size the simulation results for a single dent are shown in Table 3 and Table 4. It is obvious that the delayed probability of failure for pipeline carrying hydrogen is much higher than that for the existing natural gas pipelines. It has to be noted that as the defect size distributions proposed here are for a specific X70 pipeline and the failure probabilities will change if a different pipeline is analysed. However, it can be expected that the general trends indicated by these results will remain the same for other pipelines.

Table 3. Cumulative POF values for pipelines carrying different content of Hydrogen (a long but shallow crack initiated at the bottom of a dent)

Year	100% NG	50% NG-50% H_2	100% H_2
0	1.54E-08	1.54E-08	9.92E-06
1	1.75E-08	3.70E-08	2.77E-04
2	2.32E-08	9.00E-08	2.77E-03
3	2.57E-08	2.16E-07	1.47E-02
4	3.47E-08	4.86E-07	5.94E-02
5	4.05E-08	9.48E-07	1.43E-01
6	5.85E-08	1.91E-06	2.47E-01
7	7.13E-08	4.96E-06	3.67E-01
8	8.07E-08	1.12E-05	4.78E-01
9	9.58E-08	2.07E-05	5.55E-01
10	1.26E-07	3.64E-05	6.22E-01

Table 4. Cumulative POF values for pipelines carrying different content of Hydrogen (a short but deep crack initiated at the bottom of a dent)

Year	100% NG	50% NG-50% H2	100% H2
0	1.21E-08	1.21E-08	3.39E-05
1	1.36E-08	1.47E-08	2.44E-04
2	1.39E-08	2.48E-08	1.10E-03

3	1.41E-08	6.96E-08	2.38E-03
4	1.45E-08	1.41E-07	3.70E-03
5	1.48E-08	2.30E-07	4.82E-03
6	1.76E-08	3.30E-07	5.71E-03
7	2.02E-08	7.79E-07	6.47E-03
8	2.46E-08	1.46E-06	7.69E-03
9	2.61E-08	2.63E-06	9.51E-03
10	3.58E-08	5.73E-06	1.15E-02

By comparing the results in Table 3 and Table 4 it can also be discovered that for very short cracks in the pipeline the associated risks are lower than those for long defects even if the short cracks are deeper. Since the short cracks are less dangerous than the long cracks and we do not know the real distribution of crack sizes in the dent, the results shown in Table 3 are used to compute the failure frequency. However, adopting this approach will result in conservative results as the small cracks are implicitly treated as long cracks and thereby having the same level of contribution to the total failure frequency as the longer cracks do.

The failure frequency can be obtained by solving equation 9. Fig. 11 shows corresponding failure frequency curves for the same X70 pipeline. It has to be noted that it was assumed the dent depth is 6mm, but in fact this is not accurate as the dent depth does follow certain distribution. However, through this simplification the simulation results have already shown that adding hydrogen will increase the delayed failure frequency but it is difficult to provide an accurate estimate without more accurate data on the type of cracks initiated. Obviously the results show that reducing the amount of hydrogen added to the natural gas pipeline system reduces the risk but if inspection tools are available which can detect crack like defects the target risk level could be achieved through a carefully designed integrity management programme.

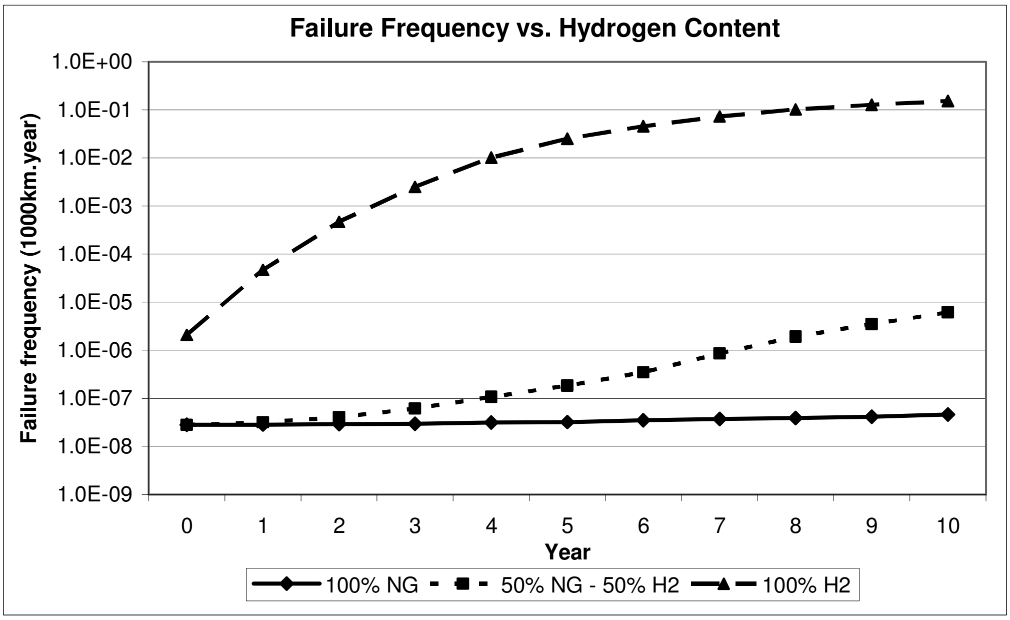

Figure 11. Failure frequency for a cracked dent in pipelines carrying NG and NG/H_2 mixtures

4.0 CONCLUSIONS

A methodology has been presented to predict the probability of failure of a pipeline subjected to third party damage is presented. It is based on the concept of the damage either initiating a crack like defect or activating a dormant crack like defect on the internal wall of the pipeline thus leading to delayed failure. The procedure is based on a probabilistic fracture mechanics approach.

The following conclusions have been drawn with regard to the determination of the failure probability for transmission pipelines conveying natural gas/hydrogen mixtures.

1) From the initial calculations the results suggest that the existence of hydrogen in a pipeline significantly increases the delayed failure probability. The reason for this is that the hydrogen penetrates the parent material through the crack surface and changes the material properties, which reduces the ability of the pipeline to resist crack growth.

2) An important element of the POF calculation is the proposed distribution of crack sizes located near the dent. Since no data is available on such distribution, some assumptions based on a series of sensitivity tests are made. Further work is required to obtain data to support further predictions.

3) Other parameters such has pressure drop ratio, number of cycles and the hitting rate are either taken from literature or design guidelines. Hence, when interpreting the failure frequency results one must realise that the failure frequency may vary significantly from pipeline to pipeline.

4) 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 are very sensitive to these inputs.

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