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EVALUATION OF PREDICTIVE ASSESSMENT RELIABILITY ON CORRODED TRANSMISSION PIPELINES

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ABSTRACT

Oil and Gas operators have to deal with the ageing process of their transmission pipeline grid. Some of these pipelines can be inspected using In Line Inspection (ILI) tools. In order to maintain an acceptable integrity level, re-inspection operations have to be performed. This process needs to be optimized in terms of resources and cost.

CRIGEN, GDF SUEZ Research and Development Center, has developed a methodology which prioritizes rehabilitation operations on a pipeline after in-line inspections, and determines the optimal interval for re-inspection. A reliable help decision software tool, GADPro, which applies the methodology has also been developed.

Dealing with defects assimilated to external electrochemical corrosion, the developed methodology is based on :

- ILI features reported in depth dimensions in order to assess a probable corrosion growth rate,
- probabilistic distribution of input parameters (defect geometrical characteristics, pipeline characteristics and corrosion growth rate),
- failure probability calculation.

The calculation results take the form of three probabilities of failure :

- a punctual probability of failure for each defect,
- an annual probability of failure for each defect,
- an annual probability of failure per kilometer of pipe.

To interpret the results, the annual probability of failure per kilometer of pipe is then compared with threshold values from safety studies that can be associated with location places and failure modes.

In year 2009, the re-inspection of two 24 inches coil tar enamel gas transmission pipeline formerly inspected in year 1999 gave the opportunity to evaluate the consistency of the predictive assessment from GADPRO tool. The first pipeline was 125 km long. The second one was 93 km long. To reach that goal, a first step consisted to match the metal losses from the two run for each pipe section. Then, corrosion growth rates were calculated from the sizing evolution of the matched defect from the two ILI runs. Results were compared with the corrosion growth rate determined with the assumptions made in GADPro tool. Finally, the preventive intervention program which could have been determined after the1999 ILI was compared to the one established using the results of the inspection performed on the same line in year 2009.

This article presents the procedures employed to carry out a probabilistic assessment of corroded pipelines inspected with ILI tools as well as the methodology validation study based on pipeline re-inspection data analysis.

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1. INTRODUCTION TO PROBABILISTIC APPROACH

In the 6th EGIG-report [1], corrosion was identified as the third main cause of incidents (15%) on gas transmission pipelines, after external interferences (50%) and construction defect/material failures (17%). Among those 15%, external corrosion represents 80% of all accidents. Indeed, wherever coatings and/or cathodic protection may fail to provide adequate protection to the external surface of the pipe, external corrosion may occur.

ILI tools are used in order to detect and size metal losses and geometrical anomalies. To optimize the re-inspection process, GDF SUEZ R&D Division has developed a probabilistic method. This method is integrated in a tool, GADpro, which is a module of the assessment software GADline® [2]. This method is based on the use of ILI data and reliability algorithms allowing the determination of the probability of failure for external corrosion defects on pipelines.

Several methodologies and associated softwares have been developed to analyze corrosion defects on transmission pipelines with a probabilistic approach. Most often, the result is based on the calculation of a single probability of failure not taking into account the consequence level in the area around the pipeline. GDF SUEZ R&D division has developed its own methodology to calculate failure probabilities associated with different failure modes. Then, these probabilities are compared to threshold values that can be associated with location places and failure modes.

2. METHODOLOGY

The analysis of corrosion defects needs several parameters such as pipeline characteristics : pipeline geometry, material properties, operating pressure, date of commissioning; but also defect properties : defect characteristics (length, width and depth).

Due to the pipe’s manufacturing process, the measurement technique or their determination process, the value of the parameters listed above is affected by an uncertainty that has to be taken into account. Instead of considering conservative values for these parameters, the probabilistic approach considers random variables defined by statistical distribution functions established through uncertainty analysis.

The use of a probabilistic approach offers several advantages: the approach is closer to reality by avoiding an excessive conservatism, it offers the possibility to define a common level of reliability on gas infrastructure, and the possibility to integrate parameters to evaluate the failure risk.

The developed methodology applied to external corrosion provides the following results :

- prioritization of the corrosion defects that need to be repaired on the basis of risk level (i.e. rehabilitation program),
- definition of a re-inspection date for ILI, subject to the respect of the determined rehabilitation program ,
- identification of the riskiest areas along the pipeline routing.

The methodology applied for this probabilistic approach is represented on Figure 1 and is described in the following paragraphs.

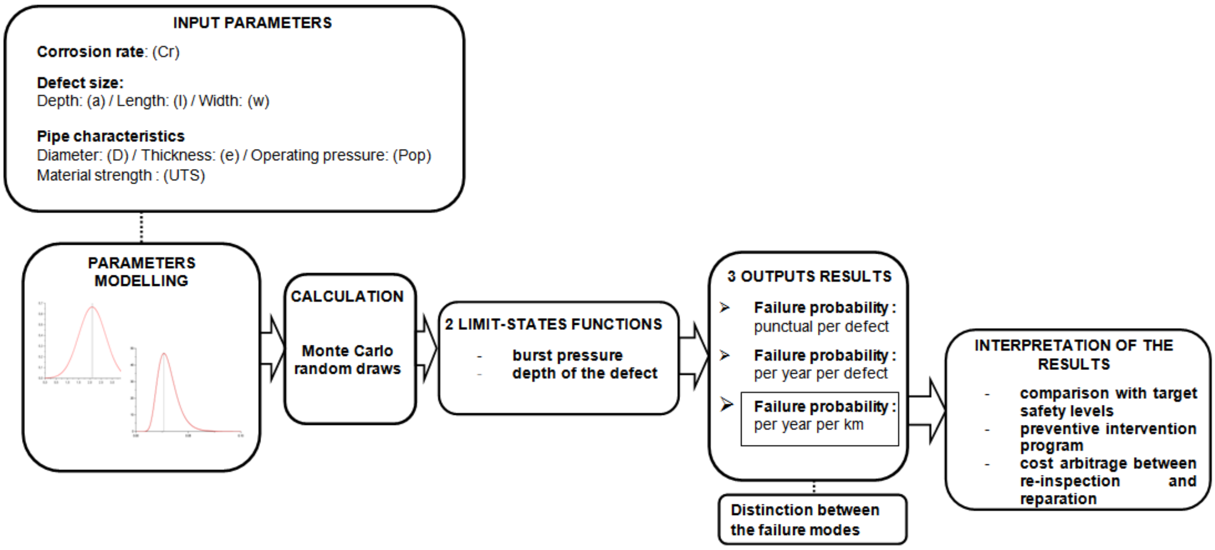


Figure 1 Schematic view of the methodology used to apply probabilistic approach

3. MODELISATION OF INPUT PARAMETERS: PROBABILISTIC DISTRIBUTIONS

The input parameters correspond to the data required to calculate the two limit-state functions (burst pressure and defect depth).

In a probabilistic approach, the accurate characterization of the probabilistic distribution of the random variables on which the probability of pipeline failure depends is extremely important in order to achieve results with a reasonable degree of confidence.

Wall-thickness and material strength are modeled with normal distributions from the SUPERB European project [3]. These probabilistic distributions use parameters (mean and standard deviation) that depend on pipe manufacturing and diameter.

The uncertainty related to the defect's geometry (depth, length and width) is modeled with a normal distribution. The parameters of the distribution are calculated based on the uncertainties of ILI measurements (e.g. Intelligent Pigs' specifications) :

- mean is deduced from pigs measurements uncertainties,
- standard deviation is deduced from pigs' measurement uncertainties and reliability rate depending on the defect's geometric classification (metal loss, pit, hole, grooving, slotting).

Pipe diameter and operating pressure are considered as constants. It is therefore possible to choose values that will guarantee the results are conservative.

Finally, in order to be conservative and based on the results of bibliographical research [4], the corrosion growth rate is modeled with a log-normal distribution. This log-normal distribution is deduced from local corrosion growth rate calculated for each external metal loss recorded by ILI on the considered pipe (See Figure 2).

Local corrosion growth rates are estimated by dividing the defect's depth by the supposed corrosion's age at the date of the inspection. In practice, it is often assumed that the corrosion starts 10 years after the pipeline date of construction. This leads to consider a conservative date of corrosion initiation.

Log-normal distribution parameters can also be directly defined by the user. This allows the use of specific distributions or "universal" distributions which have been empirically established (See Figure 2).

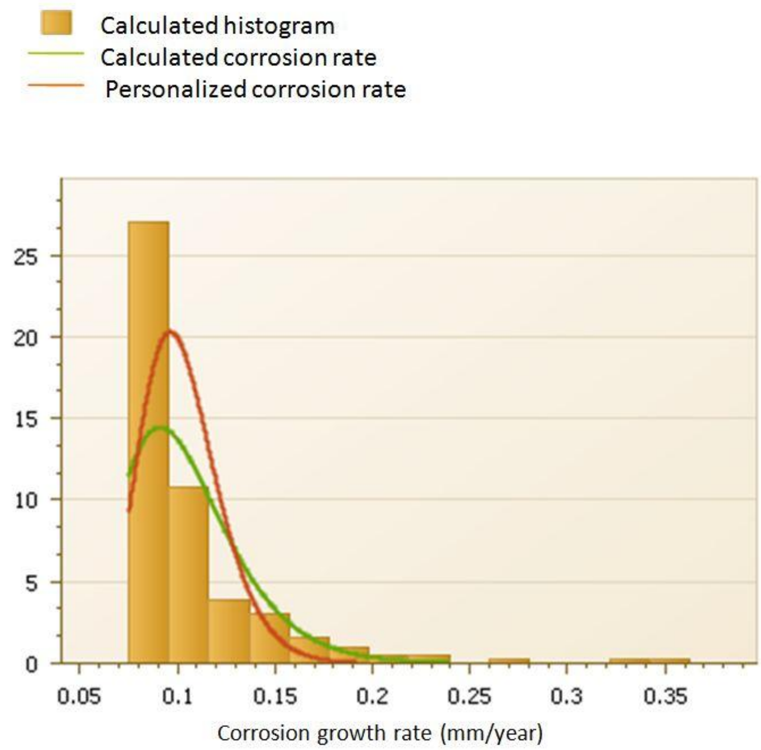


Figure 2 : Corrosion growth rate is modeled through one calculated or personalized log-normal distribution

Once the local corrosion growth rate has been calculated for each defect, it is possible to draw a graphic representing the variation of this parameter along the pipeline. If heterogeneous corrosion growth rates along the pipe are revealed, then, it is possible to divide the pipe into homogeneous sections. Then one log-normal distribution is applied for each homogeneous section.

On the case represented on Figure 3, two different log normal distributions are calculated : one is applied to section A and the other one to section B.

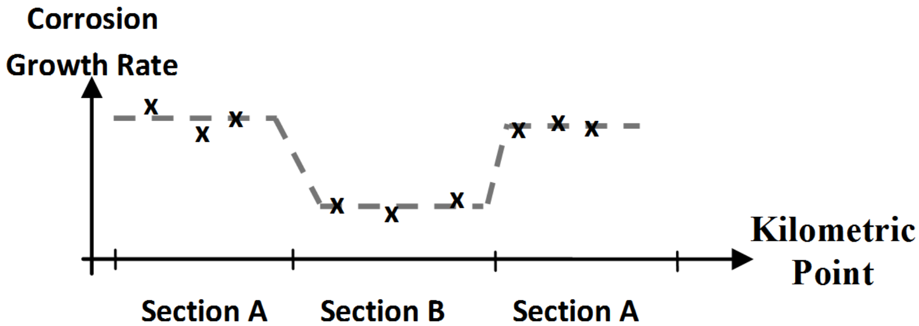


Figure 3 : Illustration of the division in homogeneous section depending on different corrosion growth rates

The calculation is made assuming that the corrosion growth rate is only in depth (*i.e.*, along the thickness of the pipe).

4. TWO LIMIT-STATE FUNCTIONS

To evaluate the acceptability of the assessed external corrosion defects their geometrical characteristics are compared with two criteria which take the form of two limit-state functions :

G1 : failure limit-state function due to internal pressure meaning the difference between predicted burst pressure for corrosion defect and operating pressure. (See Figure 4).

G2 : failure limit-state functions due to internal pressure without burst meaning the difference between metal loss due to corrosion and wall thickness which causes leaks or threatens pipeline integrity. The value is commonly selected in the 80 – 100% wall thickness range (See Figure 4)

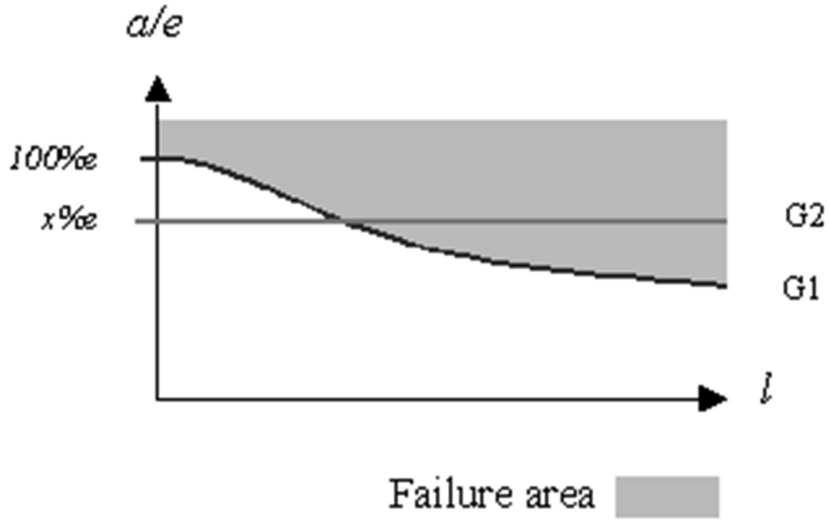


Figure 4 : Illustration of failure limit-state functions G1 and G2

These two failure limit-state functions have the following parameters : wall thickness, pipe diameter, ultimate tensile strength (mechanical strength), defect's depth and length. Their mathematical expressions are :

G1 (T) = Pop – P_{burst}*
G2 (T) = a*(T) – x%e*

With "T" representing the time and "*" indicating that the parameter is defined as a variable with a probabilistic distribution.

The burst pressure is calculated according to the standard BS7910 [5] :

$$P_{burst}^*(T) = fc1 \times fc2' \times \frac{e^* \times UTS^*}{D - e^*} \times \frac{1 - \dfrac{a^*(T)}{e^*}}{1 - \dfrac{a^*(T)}{Q^*(T).e^*}}$$

With :

fc1, modeling safety factor,
fc2', design safety factor including a coefficient established through a test campaign [6],
Q (T), defined as :

$$Q(T) = \sqrt{1 + 0{,}31.\frac{l(T)^2}{D.e}}$$

These two failure limit-state functions describe the failure area which is represented by the entire domain such as: G1 (T) < 0 or G2 (T) < 0. It is represented in gray on Figure 1.

5. CONSIDERING FAILURE CONSEQUENCES

To characterize the importance and the consequences of a failure on a corroded area, different failure modes can be introduced depending on defect geometry and on different location places. Then, different acceptance criteria can be defined depending on :

- the calculated failure mode

and/or

- the chosen location place.

The methodology can take into account different failure modes according to the surface covered by the corrosion defect. It has been assumed that the failure mode depends on the equivalent diameter of the defect, which is named “d”. The latter corresponds to the diameter of the circle which is equivalent, in terms of surface, to the area covered by the corrosion defect:

$$\pi\left(\frac{d(T)}{2}\right)^2 = w(T) \times l(T)$$

Where “T” is the date when the calculation is made.

The methodology can also take into account the location place of the defect. In the actual software, three different types of location places can be used : rural, semi-urban or urban areas for example.

These two functionalities make it possible to characterize the probability of failure per failure mode and/or per consequence area and to apply the associated threshold value.

6. CALCULATION OF THE PROBABILITY OF FAILURE

Three types of probability of failure are considered as output results :

- a punctual probability of failure for each defect,
- an annual probability of failure for each defect,
- an annual probability of failure per kilometer of pipe

For each year of the calculation, the punctual probability of failure per defect is calculated with the Monte-Carlo approach. The punctual probability of failure per defect is calculated as follows :

$$Pj\,(Ti) = \frac{\sum_p \left(w_p * I\left[P_{burst} < Pop\right]\right)}{Total\ number\ of\ random\ shots}$$

The numerator of the formula represents the number of random shots when the defect is calculated in the failure area. This probability is calculated for each defect and for each year.

If needed, this punctual probability of failure can also be calculated for different failure modes. Indeed, as described in the paragraph 5 “considering failure consequences”, different failure modes can be introduced : for instance, scenarios of small, medium or large leaks although the small leak failure mode is the most representative scenario used for corrosion defect.

In the eventuality of three failure modes (small, medium or large leak for instance), three types of punctual probability of failure would be calculated for a defect j at date T_i :

- the punctual probability of failure by small leak (P_j^1 (T_i))
- the punctual probability of failure by medium leak (P_j^2 (T_i))
- the punctual probability of failure by large leak (P_j^3 (T_i))

Then, the total punctual probability of failure is obtained through the following formula :

$$P_j^0\,(T_i) = P_j^1\,(T_i) + P_j^2\,(T_i) + P_j^3\,(T_i)$$

The total punctual probability of failure represents the probability that the defect (j) reaches the failure area whatever the failure mode.

Then the annual probability of failure for each defect is calculated :

$$pof_j\,[T_i;T_{i+1}] = \frac{p_j(T_{i+1}) - p_j(T_i)}{1 - p_j(T_i)}$$

The annual probability of failure of a defect (j) represents the probability that (j) reaches the failure area in the course of the [Ti ; Ti+1] period. This probability is calculated for each defect. It is calculated with the punctual probability of failure in each failure mode that is considered as well as with the total punctual probability of failure.

Finally, the annual probability of failure per kilometer of pipe is calculated :

$$POF\,[T_i;T_{i+1}] = 1 - \prod_j \left(1 - pof_j\left[T_i;T_{i+1}\right]\right) \qquad (1)$$

This result corresponds to the probability that a failure occurs on one kilometer during the [Ti ; Ti+1] period. In this formula, (j) represents all the defects that belong to the considered kilometer.

The methodology considers as many kilometers as there are corrosion defects on the pipe : each defect corresponds to the beginning of a kilometer.

This formula (1) is applied to calculate the total annual failure probability as well as to calculate the annual probability of failure for each considered failure mode.

7. INTERPRETATION AND USE OF THE RESULTS

To interpret the results, the annual probability of failure per kilometer of pipe is compared with threshold values. These threshold values describe the acceptable probability of occurrence of one failure in one location place and/or in one considered failure mode.

The year and the defect, or defects, that make a kilometer of pipeline become critical are identified. These defects can also be integrated in a preventive intervention program that can be integrated into the initial reparation campaign following the ILI.

The obtained results can also be used in order to optimize the re-inspection program for it to be more cost-effective. Indeed, the run of an intelligent pig is an expensive operation. Not only because of the cost of the pigging operation, but also because of the cost of the temporary reduction of the gas delivery through the transmission pipeline.

8. EVALUATION OF THE ASSESMENT RELIABILITY BASED ON TWO SUCCESSIVE ILI FILES (1999 AND 2009)

8.1. What is matching?

The matching consists in finding a link between the ILI data for two (or more) runs on the same line. It’s practically not an automated process, as a lot of human operations is required.

In our case, a specific approach, based on the distance offset and the defects o’clock positions analysis, was used. This process is described in the Figure 5 below.

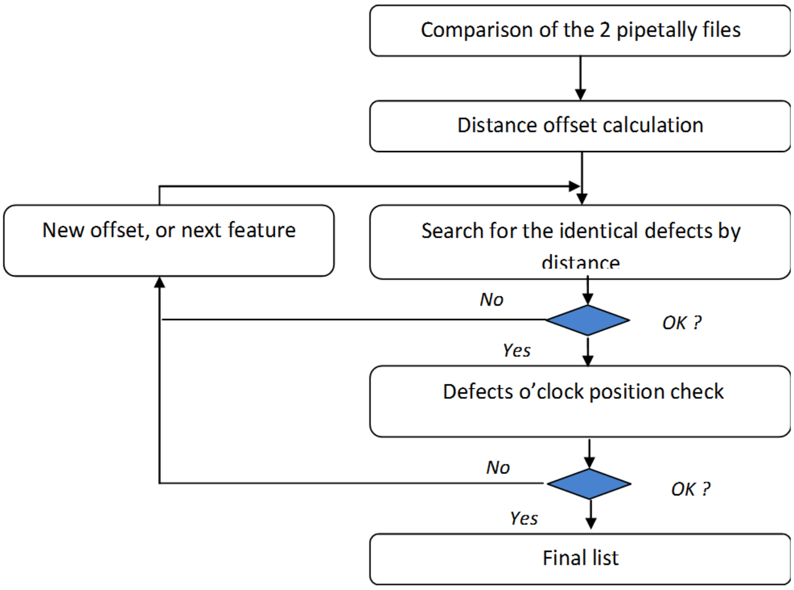


Figure 5 : Matching process

The study of the data files showed that this operation can be a difficult task. One of the reasons is that the distance offset value can change along the line, as shown on the figures 6 and 7 below. The offset value is determined by comparing specific points position on the two pipetally files.

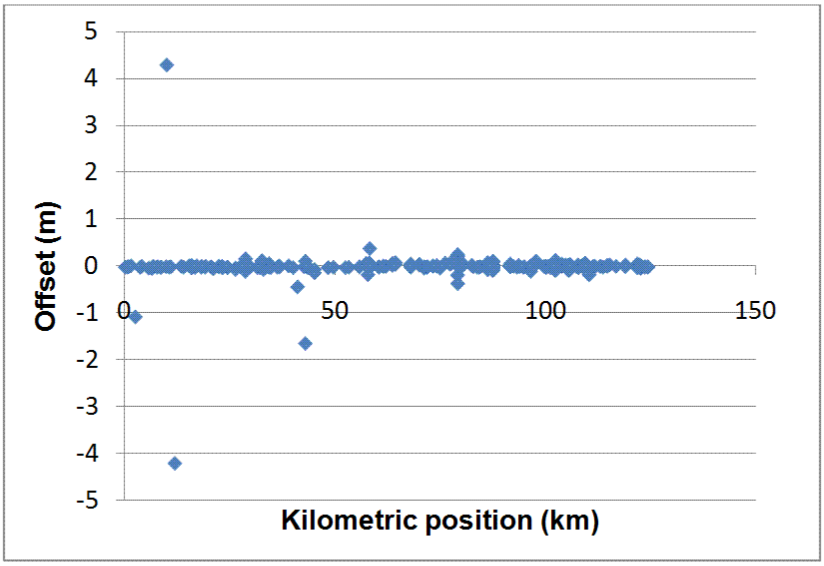


Figure 6 : Offset along the pipeline A

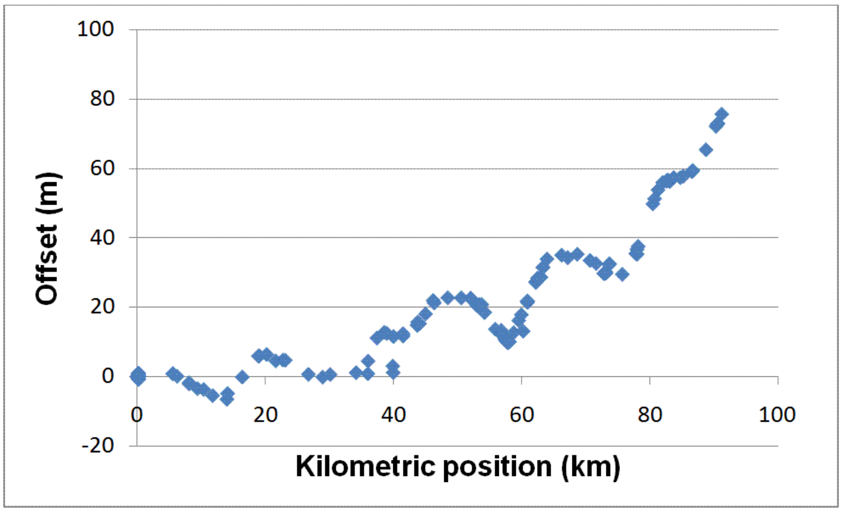


Figure 7 : Offset along the pipeline B

However, the matching was possible for:

- 50% of the 1999 features, for the pipeline A
- 40% of the 1999 features, for the pipeline B

But, in most of the cases, the classification of the defects is different between the two log files. For instance, for the pipeline A, 24 defects among the 531 matched defects, are classified as corrosion in 1999 and in 2009. Consequently the number of matched defects is sometimes very limited.

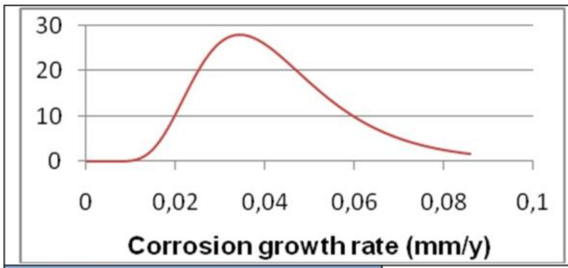
This result is probably mainly due to technologies evolution which induces significant differences in term of performances between two runs done within 10 years.

8.2. Corrosion growth rate calculation and comparison

Four methods were studied to calculate the external corrosion growth rate on those two pipelines:

8.2.1. Corrosion growth rate mean value for the 1999 run.

This calculation will allow the build of a preventive inspection as it could have been done in 1999.



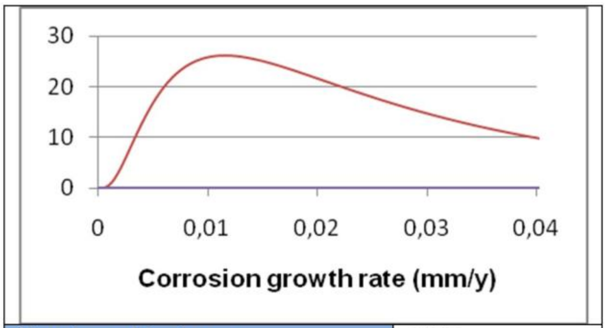
Number of features	200
Mean value	43 µm/y
Standard deviation	17 µm/y

Figure 8 : Corrosion growth rate calculation for the 1999 Pipeline A log file

It is important to note that the detection threshold of the ILI is higher in 1999 than in 2009. This fact can lead to overestimate the corrosion growth rate compared with 2009.

8.2.2. Corrosion growth rate mean value for the 2009 run, when considering this run as the first run.

This calculation allows the build of a preventive inspection program based on the actual knowledge of the pipeline condition.

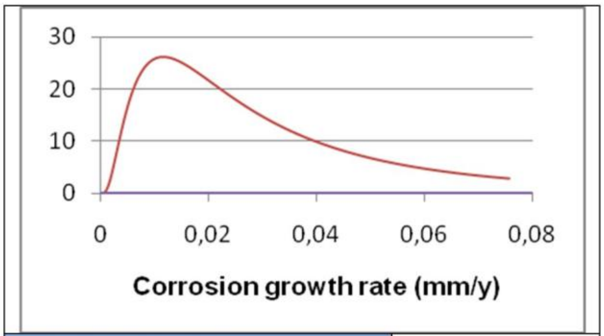


Number of features	1129
Mean value	17 µm/y
Standard deviation	7 µm/y

Figure 9 : Corrosion growth rate calculation for the 2009 Pipeline A log file

8.2.3. Corrosion growth rate mean value for the features which matched in the two runs in 1999 and 2009.

This gives us information about the corrosion growth rate evolution between 1999 and 2009.



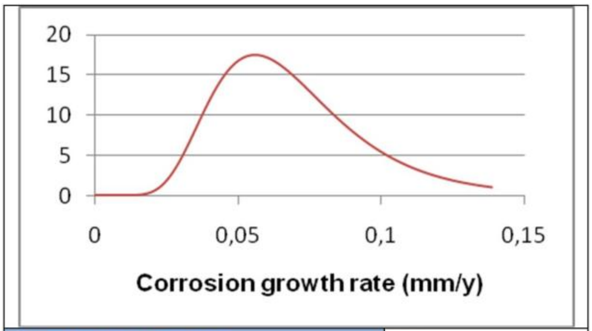
Number of features	17
Mean value	38 µm/y
Standard deviation	42 µm/y

Figure 10 : Corrosion growth rate calculation for defects of the Pipeline A which matched

As illustrated on the picture above, the few number of feature leads to a high standard deviation. For some features, the depths reported in the log files are higher in 1999 than in 2009. This gives, in theory, a negative corrosion growth rate. Therefore these features were excluded of the analysis.

8.2.4. Corrosion growth rate mean value for the features which didn't matched in the two runs in 1999 and 2009.

This rate can be interpreted as the corrosion growth rate of defects which "appeared" after 1999. The defects which were considered were located more than 1 meter from matched defects. This precaution is taken in order to ensure that these defects are not a part of a matched defect which was not detected in 1999 due to the higher detection threshold.



Number of features	443
Mean value	69 µm/y
Standard deviation	27 µm/y

Figure 11 : Corrosion growth rate calculation for defects of the Pipeline A which appeared after 1999

In brief, the following results were observed:

- As expected, the 2nd method gave a lower rate than the 1st method, this confirms that the corrosion growth rate tends to decrease over time and that the cathodic protection is efficient.

- The rate calculated with the 3rd method is between the rates of the 1st and 2nd methods

- The highest corrosion growth rate is given by the 4th method.

8.3. Preventive intervention programs, Pipeline A

8.3.1. Preventive intervention program based on the 1999 ILI log file, Pipeline A

This program could have been built by the operator in 1999 if the probabilistic assessment approach was developed.

We considered all the features classified as corrosion in the 1999 log file, plus all the features from the 1999 log file, which were classified as corrosion in the 2009 log file (matched features).

The first corrosion growth rate calculation method was used (method presented in the paragraph 8.2.1. , i.e. rate from the 1999 features only).

The results are sum up in the following diagram.

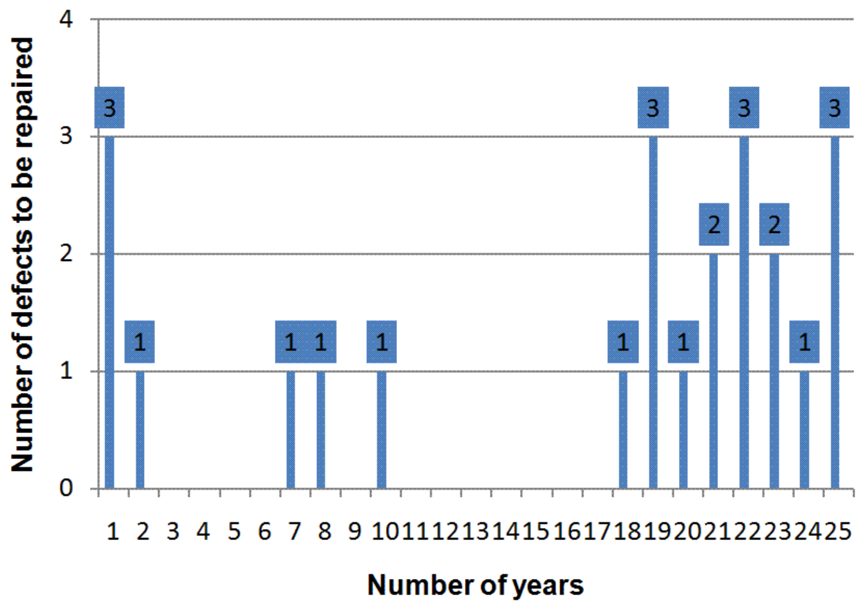


Figure 12 : Number of defects to be repaired over 25 years after 1999, Pipeline A

The analysis of these results, compared with the repaired defects list, gives us the following situation.

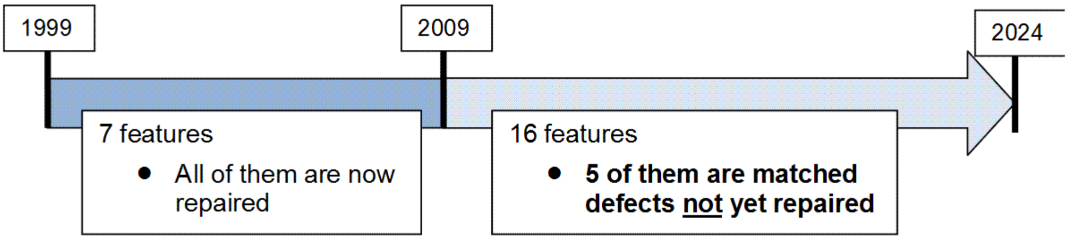


Figure 13 : Situation over 25 years after 1999, Pipeline A

Among the 16 features which are supposed to be repaired after 2009, 5 of them are matched defects that are not yet repaired. Those defects are interesting to compare 1999 results with 2009 results.

8.3.2. Preventive intervention program based on the 2009 ILI log file, Pipeline A

This program is the one that could be built now by the network operator.

We considered all the features classified as corrosion in the 2009 log file. Two corrosion growth rate calculations were used:

- On one hand, the 3rd calculation method was used for 2009 features that matched with 1999 features (method presented in the paragraph 8.2.3., i.e. rate from the matched features)

- On the other hand, the 4th calculation method was used for 2009 features that didn't matched with 1999 features (method presented in the paragraph 8.2.4., i.e. rate from the not matched features)

The results are sum up in the following diagram.

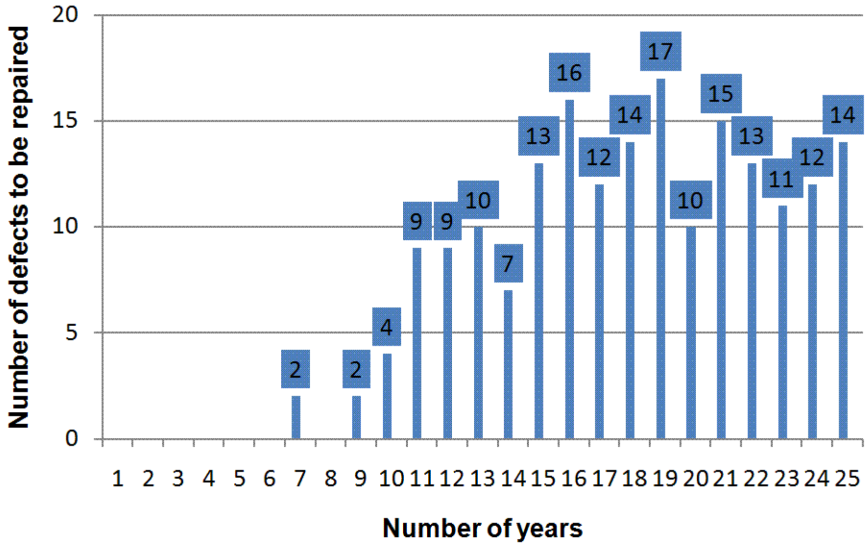


Figure 14 : Number of defects to be repaired over 25 years after 2009, Pipeline A

The analysis of these results, compared with the repaired defects list, gives us the following situation.

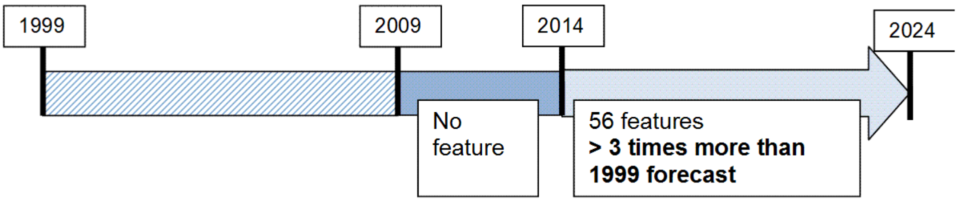


Figure 15 : Situation over 25 years after 2009, Pipeline A

- No feature has to be repaired before 2014 (5 years after the re-inspection).

- 56 defects have to be repaired on the 2014-2024 period of time.

8.3.3. Comparison of the 2 preventive intervention programs, Pipeline A

The difference between the two log files, in terms of number of features to be repaired after 2009, is mainly due to features that were not detected in 1999. This could be explained by the performance gap between the two runs, especially the detection threshold which decreased from 10% to 5% of the pipeline thickness.

According to the 1999 log file, 5 matched defects are not yet repaired but are supposed to be repaired after 2009.

According to the 2009 log file, the first defect to be repaired has to be repaired before 2016 (7 years after the re-inspection). This first defect to repair is one of the 5 matched defects, its date of reparation is supposed to be done sooner (4 years sooner) than it was forecast in 1999.

Consequently the re-inspection period of time for this particular pipeline (pipeline A) shall not to exceed 17 years.

8.3.4. Preventive intervention programs, Pipeline B

The same method is applied to the Pipeline B data, the results are presented here below.

8.3.5. Preventive intervention program based on the 1999 ILI log file, Pipeline B

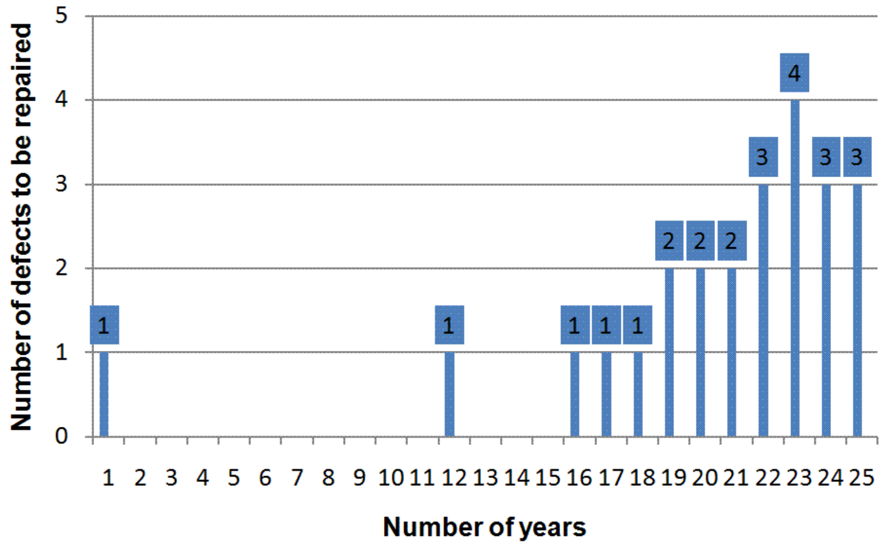


Figure 16 : Number of defects to be repaired over 25 years after 1999, Pipeline B

The analysis of these results, compared with the repaired defects list, gives us the following situation.

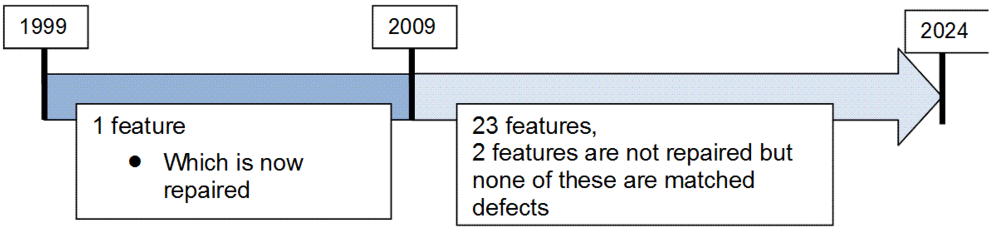


Figure 17 : Situation over 25 years after 1999, Pipeline B

Among the 23 features which are supposed to be repaired after 2009 and are not yet repaired, none of them are matched defects. Unfortunately we cannot do the same analysis as for the pipeline A.

8.3.6. Preventive intervention program based on the 2009 ILI log file, Pipeline B

Only the 4th calculation method was used for all the features (method presented in the paragraph 8.2.4., i.e. rate from the not matched features). Indeed, there were not enough matched defects to calculate the corrosion growth rate following the 3rd method (method presented in the paragraph 8.2.3., i.e. rate from the matched features)

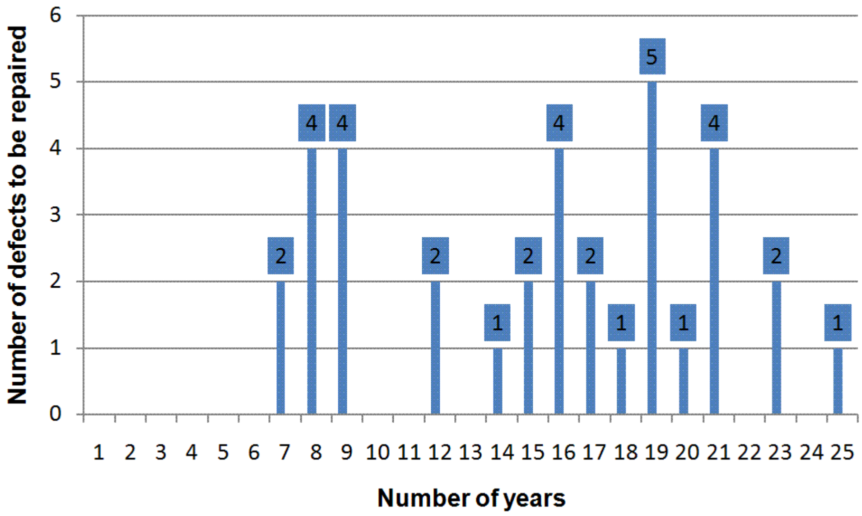


Figure 18 : Number of defects to be repaired over 25 years after 2009, Pipeline B

The analysis of these results, compared with the repaired defects list, gives us the following situation:

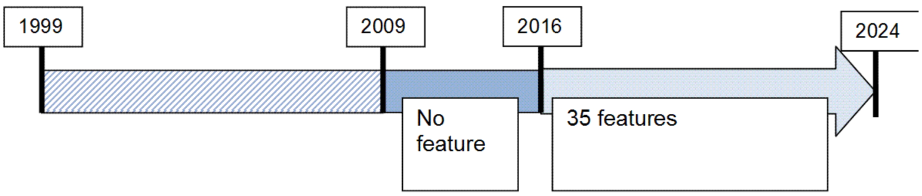


Figure 19 : Situation over 25 years after 2009, Pipeline B

- No feature has to be repaired before 2016 (7 years after the re-inspection).
- 35 defects have to be repaired on the 2016-2024 period of time.

8.3.7. Comparison of the 2 preventive intervention programs, Pipeline B

According to the 2009 log file, the first defect to be repaired has to be repaired before 2016 (7 years after the re-inspection).

Consequently the re-inspection period of time for this particular pipeline (pipeline B) shall not exceed 17 years.

9. CONCLUSION

The study of the successive inspections data highlighted:

- The importance of making the appropriated choice for the corrosion rate calculation method, when dealing with two successive ILI runs

- The importance of the matching process.

If these two first steps are not correctly done, the risk of building a wrong preventive intervention program exists, by considering a low corrosion growth rate.

The methodology, presented in the article, allowed to justify that the re-inspection period of time for these two particular pipelines shall not exceed 17 years, but the hypothesis which were taken probably leads to overestimate the corrosion growth rate of the defects that didn't match. Indeed these defects are supposed not to be detected in 1999, and were supposed to be created in 1999, although the performances of the two runs are not completely comparable, especially the detection threshold value.

NOMENCLATURE

Symbol	Definition	Unit
P_{burst}	Burst pressure	MPa
P_{op}	Operating pressure	MPa
a	Defect depth	mm
e	Wall thickness	mm
UTS	Ultimate Tensile Strength	MPa
D	External pipeline diameter	mm
w	Defect width	mm
l	Defect length	mm
w_p	Weight factor	-
d	Diameter of the circle equivalent to the defect surface	mm
Cr	Corrosion growth rate	mm/year
$P_j\,(T_i)$	Probability of failure of a (j) defect at the date (T_i)	-
$Pof_j[T_i\,;\,T_{i+1}]$	Annual probability of a (j) defect	-
$POF[T_i\,;\,T_{i+1}]$	Annual probability of failure per kilometer	-
Q	Modified Folias factor	-
fc1	Modeling safety factor	-
fc2’	Design safety factor	-
T_0	Year of ILI	year
T_i	Year i after ILI	year

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