23rd World GAS Conference, Amsterdam 2006

FUTURE INTEGRITY MANAGEMENT STRATEGY OF A GAS PIPELINE USING BAYESIAN RISK ANALYSIS

A Ainouche

ALGERIA

ABSTRACT

Pipelines have long been considered the safest and most cost-effective means of transporting gas over long distance. Corrosion is the primary reason for aging and deterioration of a buried gas pipeline. Without a best practices corrosion prevention strategy, corrosion will continue and the cost of repairing a deterioration pipeline will escalate. Significant savings are possible by optimizing the inspection and corrosion prevention strategies. In order to achieve such optimization, improved prediction models for internal corrosion need to be developed.

Pipeline operators need inspection techniques that help ensure the integrity of their existing pipeline systems. Significant progress in line inspection tools ("smart pigging") allows at the present time the detection and the localization of practically all the defects of corrosion and their dimensions. The majority of these tools use techniques of Magnetic flux leakage (MFL) or Ultrasonic (UT). The principal parameter in a step of quantification of the failure risk on a corroded pipeline lies in the most precise possible knowledge of the corrosion speed. The complexity of the phenomenon of corrosion, its random nature makes difficult the modeling of these parameters. The diagnosis by single inspection provides only one static image of the state of degradation of a pipeline. In the current state of knowledge, the follow-up and the prediction of the evolution of the technical state of a pipeline according to time, in particular the speed of corrosion, are theoretically possible only with a minimum of two successive inspections. However, the operations of inspection are expensive and their programming must be done by taking account of generally limited resources available.

We show in this article how a Bayesian step of modeling of the kinetics of corrosion, associated to the data resulting from only one inspection allows to obtain a credible evaluation of the risk. For that, all information available are given in terms of probability in the form of a priori gamma distribution. The inference of a posteriori distribution, on the basis of judgment of experts makes it possible to establish a statistical model of the kinetics of each point of corrosion and the estimate of the probability associated to the risk of failure.

The Bayesian approach consists in modeling the uncertainty which one has on the occurrence of an event, on the basis of a value of subjective probability a priori evaluated, then to deduce a probability a posteriori corrected by lately acquired information. This methodology makes it possible to highlight the particularity of each point of corrosion of the pipeline object of the diagnosis. This type of result is currently provides just by the operators only under the requirement of a minimum of two inspections. It also makes possible to envisage the evolution of the metal losses in time and thus to foresee an optimal planning of the maintenance actions tending to bring back the failure risk of the pipeline to an acceptable level. This approach can assist pipeline operators in defining the future integrity management strategy and in maintaining the integrity of their gas pipelines while optimizing In Line inspection intervals, resulting in cost-effective pipeline integrity management.

TABLE OF CONTENTS

1. INTRODUCTION

Internal and external corrosion affects many hydrocarbon pipelines. It is the principal cause of leaks of products and pipeline rupture, resulting sometimes in catastrophic damage (human damage, pollution of the natural environment, additional costs for repair, prolonged stop of pumping, etc). The impact of this phenomenon on the national economies, as well of producer countries as consumers, can reach very significant proportions [1]. Significant progress in the field of the in line diagnosis, mainly in the design of ILI-tools allow at the present time the detection and the localization of practically all the defects (internal and external corrosion, cracks, bumps, ovalization, etc.) and their dimensions. So, preventive interventions can limit the risks considerably. Internal corrosion is generally caused by chemical attacks of the pipeline area. External corrosion is in the majority of the cases the result of phenomena of electrochemical and chemical type. The protection of the pipelines against external corrosion is done by coating of the pipelines and cathodic protection. The principal factors supporting this type of corrosion are the defects in the coating of the pipeline, the insufficiencies of the cathodic protection system and the aggressiveness of the ground.

The detection of metal losses and crackings is the field where the use of intelligent pigs knew the most interest. Two techniques emerged:

- Detection by MFL technique (Magnetic flux leakage),
- Detection by UT technique (ultrasonic technique).

2. ESTIMATION OF THE CORROSION SPEED

The principal parameter in a step of quantification of the failure risk on a corroded pipeline lies in the most precise possible knowledge of the corrosion speed. The guiding principle of the estimation of the corrosion speed, for a pipeline having undergone two or several inspections, is based on the knowledge of the evolution of the corrosion depth according to time. The developed approaches can be summarily classified in two categories:

- ➢ Deterministic approach,
- ➢ Statistical approaches.

- **Deterministic approaches**

The deterministic estimation (figure1) supposes an evolution linear and independent of time of the corrosion speed which is then calculated by the following simple relation:

$$V=\frac{\Delta d}{\Delta \xi} \qquad (1)$$

where:

Δd : difference between the depth of the corrosion point measured during the first and the second inspection.

$\Delta\xi$: interval of time between two inspections.

This approach also allows an estimation of the date of corrosion beginning ξ_p, as well as the limiting date of intervention to avoid the failure ξ_r [2].

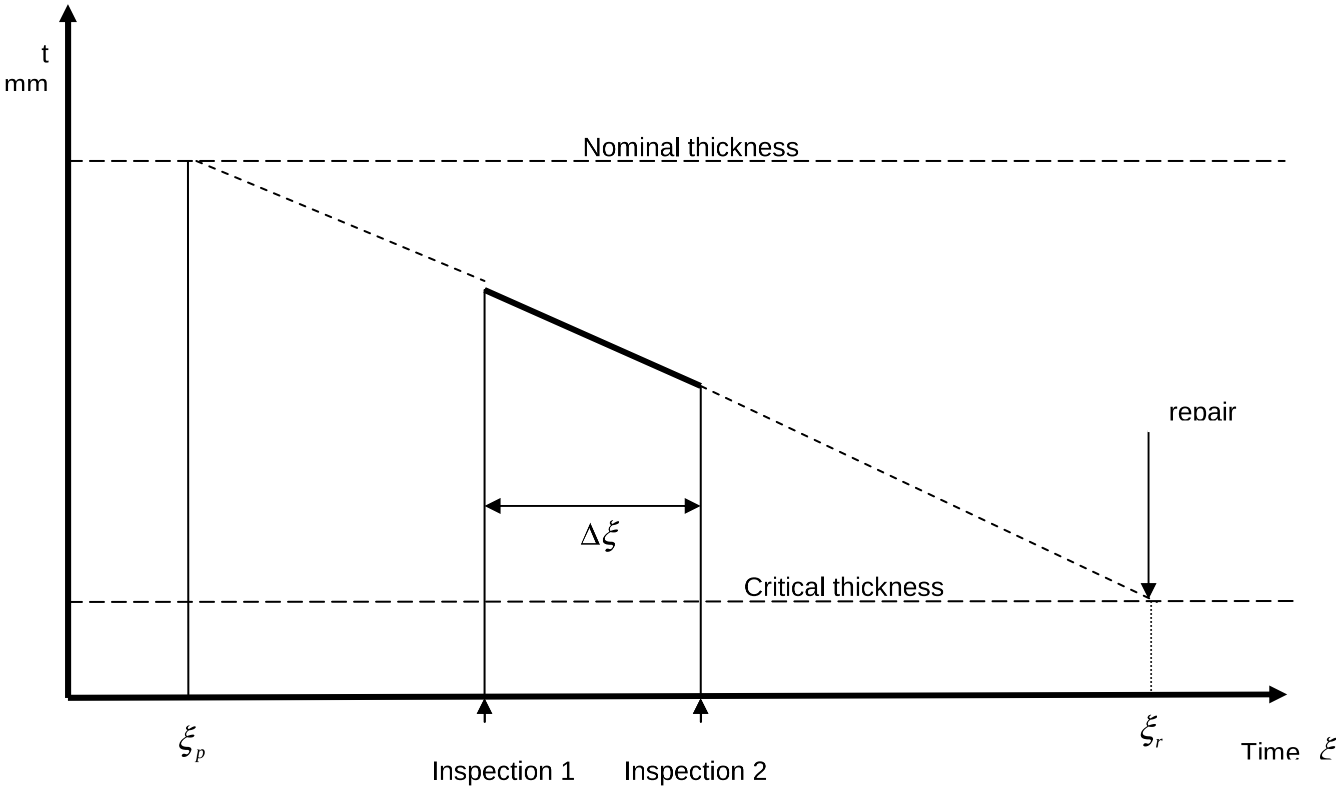

Fig 1: Deterministic estimation of the corrosion speed on the basis of two inspections

- **Statistical approaches**

In a corroded pipeline, each pipe part can contain several hundreds, see several thousands, points of corrosion of various dimensions. Under the requirement of a minimum of two inspections, the assessment of the state of corrosion can then be done on the basis of classical statistical treatment. This treatment can be formulated by one or all the following characteristics (figure 2) :

- statistical distribution of the metal losses and the speed of corrosion,
- average of the metal losses and mean corrosion speed,
- maximum value of the corrosion speed for a given significance level.

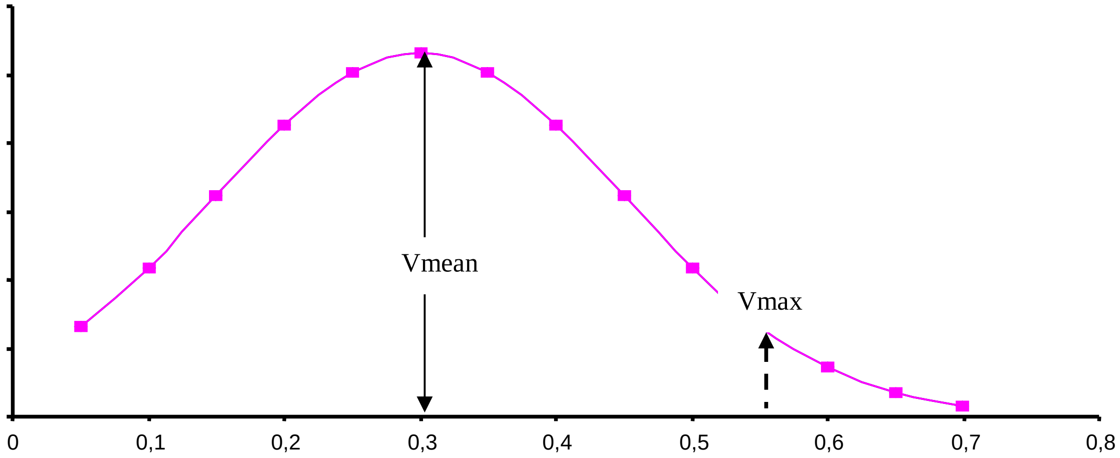

Fig.2: Statistical estimation of the corrosion speed on the basis of two inspections.

3. CASE OF A SINGLE INSPECTION

The data processing resulting from two or several inspections on the same pipeline makes it possible to draw rich information, likely to provide a credible assessment of the risk. Certain oil companies developed on this basis specific software tools [3]. In the other hand, the diagnosis by single inspection provides only one instantaneous image of the state of degradation of a pipeline. Indeed, the prediction of the evolution of the technical state of a pipeline according to time, in particular the speed of corrosion, is theoretically possible only with a minimum of two successive inspections. However, the operations of inspection are expensive and their programming must be done by taking account of most often limited available resources. In this context, it is necessary to answer to the following crucial questions:

- ☐ how to extract the maximum information on the basis of only one inspection?
- ☐ can one obtain such a rich and sufficiently credible information with only one inspection?

The answer to those questions enables to reduce the number of inspections and by this fact, the high costs associated to those operations. The results of an inspection are given in the form of a table where figure mainly the geometrical position of the corrosion points and their dimensions. Consequently, the estimation of the corrosion speed on the basis of single inspection would theoretically require the knowledge of the date of beginning of corrosion of each point. The pipeline being buried, the knowledge of this parameter is not likely to be able to be defined with exactitude. The solutions recommended to date are directed towards one of the three following basic assumptions:

- ☐ to consider that corrosion started as the putting into exploitation of the pipeline,
- ☐ heuristic estimation of the date of corrosion beginning:

$$V = \frac{d}{\xi} \tag{2}$$

- ☐ raw extrapolation of data resulting from pipelines having undergone several inspections.

The estimation of the corrosion speed by one of these approaches can result in dangerous under-assessments for the installation security or over-estimation resulting in useless and expensive repairs.

4. BAYESIAN APPROACH OF THE CORROSION SPEED ESTIMATION

The Bayes theorem is a simple consequence of the axioms and definition of the conditional probabilities. Consequently it would be possible to use it to evaluate the subjective probabilities by taking account at the same time of the estimation a priori of these probabilities and their validation by the feedback of experience. The Bayesian approach summarily consists in introducing judgments of the heuristic type into the assessment of the probability of a given proposal. This approach consists in modeling the uncertainty which one has on the occurrence of an event, on the basis of a value of subjective probability evaluated a priori, on the basis of available information, then to deduce a probability corrected a posteriori by lately acquired information. The use of data resulting from other pipelines, evolving under an environment and different operating conditions, and their raw application for the estimation of the corrosion speed of a given pipeline can result in significant errors. On the other hand, these data could constitute an excellent source of information a priori that it is necessary to adapt to the treated concrete case. The integration of complementary data , mainly those relative to the inspected pipeline age, will enable too to reinforce substantially the quality of estimation.

It thus rises from these opening remarks that there would be advantage to privilege approaches of the subjective type in the estimation of corrosion speed. The approaches to be developed in this context must take into account of the nature of information a priori available and the data on the depths of corrosion taken during a single inspection. Information available, likely to be used a priori, can take various forms. This one can be presented in particular under the aspects of judgements of experts expressed in the form of interval framing an average value of the corrosion speed. Martz and Waller developed an approach making possible to use the judgements of experts, provided in the form of intervals associated with a confidence rate, as information a priori [10,12]. However, the first difficulty related to the use of judgements of experts lies in the assessment of the probability a priori. Indeed, for the same event this one will be able to take different values according to the available expertise. In this context, the integration of complementary data resulting from other sources:

- statistical distribution of the corrosion speed resulting from a treatment of results of pipelines having undergone several inspections,
- analytical models of forecast of the corrosion speed,

Such a step would allow to reinforce the quality of the estimate considerably. But to be able to be used for the Bayesian estimation, the information a priori, opinion of experts or others, must be able to be represented in the form of statistical law of distribution. The experience gained during the processing of data resulting from pipelines having undergone several inspections, shows that the distribution of the density of probability of the corrosion speed follows a truncated normal law. This form of distribution is more convenient to represent by the intermediary of a Gamma law:

$$f(V,\beta_0,\theta_0)=\frac{\theta_0^{\beta_0}}{\Gamma(\beta_0)}V^{\beta_0-1}Exp(-V\theta_0) \tag{3}$$

V : corrosion speed

θ_0 : scale parameter

β_0 : form parameter

The choice of a distribution a priori gamma is justified by the great diversity of its representations. Thus the exponential law and the normal law represent particular cases of the Gamma laws family.

5. DETERMINATION OF THE DISTRIBUTION A PRIORI OF THE CORROSION SPEED

While considering that the pipeline had undergo only one single inspection, the determination of the distribution a priori of the corrosion speed passes by the following steps:

1- Choice of a distribution a priori gamma of the corrosion speed modeling the available information coming from judgments of experts or from results of inspection realized on other installations. In the two cases those information may be expressed in the form of $\lfloor V_{\min\_b}, V_{\max\_b} \rfloor$ interval .

2- Correction of those intervals taking into account the age of the pipeline *T* and the mean corrosion depth d_{mean} corresponding to each area.

$$V_{\min} = \max\left\{\frac{d_{mean}}{T-1}, \quad V_{\min\_b}\right\} \tag{4}$$

$$V_{\max} = \min\left\{\frac{d_{mean}}{1}, \quad V_{\max\_b}\right\} \tag{5}$$

3 - Identification of parameters β_0 and θ_0 of the distribution a priori Gamma law by solving an optimization model, built on the basis of a significance threshold of 5 %.

4 - To express the corrosion speed a priori by the relation which follows :

$$f(V) = \frac{\theta_0}{\Gamma(\beta_0)} \cdot V^{(\beta_0 - 1)} \cdot Exp(\theta_0 \cdot V) \tag{6}$$

6. ESTIMATION OF THE MOST PROBABLE TIME OF CORROSION BEGINNING

In a homogeneous area of corrosion the points of corrosion are not judicious to appear at the same period. Reasonably, those points should appear in different periods during the exploitation duration, these the need to give in the form of probability the duration of the corrosion beginning and to present it in the form of a probability distribution which will enable us to draw up an estimation of the most probable duration of the corrosion beginning.

However, to obtain the law of distribution of the durations of corrosion beginning we had recourse to the procedure here below, based on the theory of the functions of random argument [13].

$$g(\xi) = \frac{d_{mean}}{\xi^2} \frac{\theta_0}{\Gamma(\beta_0)} \cdot \left(\frac{d_{mean}}{\xi}\right)^{(\beta_0 - 1)} \cdot Exp\left(\theta_0 \cdot \frac{d_{mean}}{\xi}\right) \tag{7}$$

To determine the time of the most probable of corrosion beginning we will use the following model of optimization :

$$\frac{d_{mean}}{\xi^2} \frac{\theta_0}{\Gamma(\beta_0)} \cdot \left(\frac{d_{men}}{\xi}\right)^{(\beta_0 - 1)} \cdot Exp\left(\theta_0 \cdot \frac{d_{mean}}{\xi}\right) \Rightarrow Max \tag{8}$$

7. DISTRIBUTION A POSTERIORI OF THE CORROSION SPEED

The distribution a priori enables to model the information derived from an experience acquired on other pipelines. However, the use of the Bayesian inference makes possible to deduce the distribution a posteriori of the corrosion speed by considering the information resulting from our own experience for each corrosion point in order to approach the field reality. Being given that the distribution a priori selected is a gamma law of parameters β_0 and θ_0 consequently, the distribution a posteriori of the corrosion speed will be only a Gamma law of parameters $(d_i + \beta_0)$ and $(\xi_p + \theta_0)$ and is expressed :

$$f(V)=\frac{(\theta_0+\xi_p)^{(\beta_0+d_i)}}{\Gamma(\beta_0+d_i)}\cdot V^{(\beta_0+d_i-1)}\cdot Exp\left(-(\theta_0+\xi_p)V\right) \tag{9}$$

This last relation is the expression of a gamma law of $(d_i+\beta_0)$ and $(\xi_p+\theta_0)$ parameters where d_i represents the corrosion depth of the considered point and ξ_p the date of corrosion beginning.

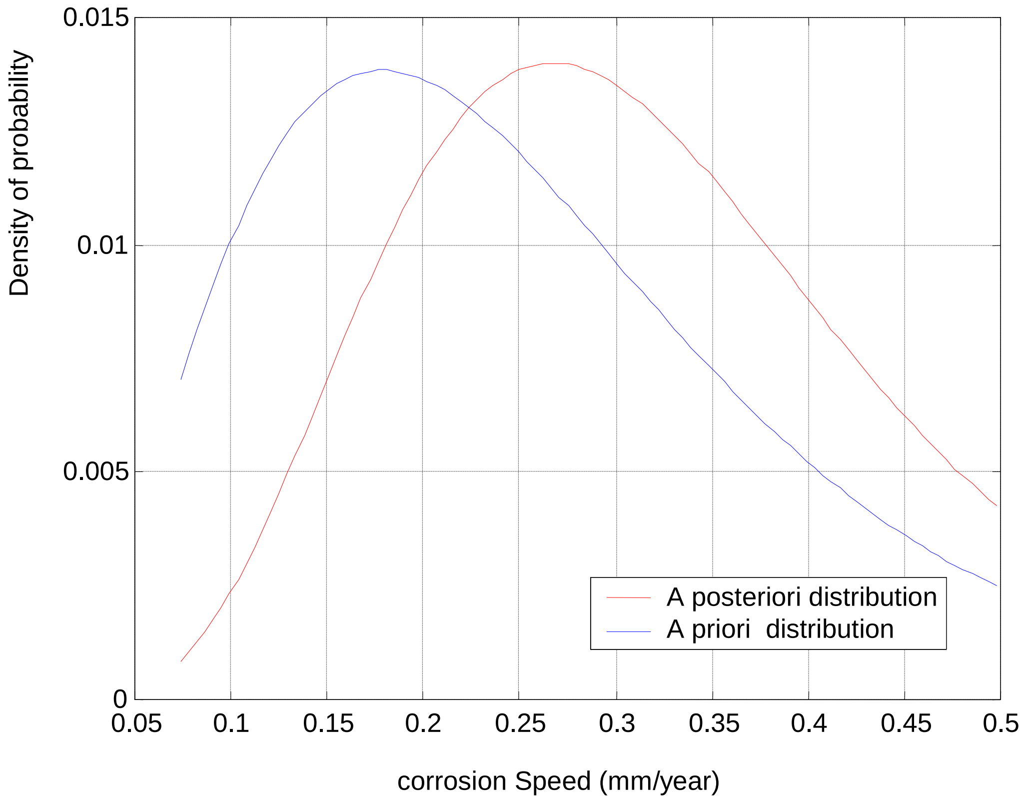

Fig 3 : A priori and A posteriori distribution of the corrosion speed

Relation (9) enables the estimation of the speed distribution law individually for each corrosion point (figure 3). At the present time , this type of results is provided by operators only on the basis of multiple inspections.

8. DISTRIBUTION OF CORROSION DEPTH EVOLUTION WITH TIME

The determination of the distribution a posteriori of the speed for each corrosion point enables to foresee the possibility to express the corrosion depths evolution in function of time τ in the form of distribution laws. The general expression of those laws, obtained too by the mean of the random argument functions theory, is the following :

$$f(V)=\frac{(\theta_0+\xi_p)^{(\beta_0+d_i)}}{\Gamma(\beta_0+d_i)}\cdot V^{(\beta_0+d_i-1)}\cdot Exp\left(-(\theta_0+\xi_p)V\right) \tag{10}$$

Where:

d_i , is the corrosion depth at date of inspection

The relation expressing the law of depths distribution and their evolutions in time is given as follows:

$$g(d)=\frac{(\theta_0+\xi_p)^{(\beta_0+d_i)}}{\Gamma(\beta_0+d_i)\cdot\tau}\cdot\left(\frac{d-d_i}{\tau}\right)^{(\beta_0+d_i-1)}\cdot Exp\left(-(\theta_0+\xi_p)\cdot\left(\frac{d-d_i}{\tau}\right)\right) \tag{11}$$

9. LIMIT STATE FUNCTION AND FAILURE RISK

For the analysis of a pipeline reliability, it is necessary to define the failure function. In this context, dimensions of the metal loss are taken as load conditions and acceptable dimensions of the defect as resistance conditions. The equality of the load and resistance characterizes the limit state. When the load is higher than resistance, the failure occurs.

As deterministic model of failure one generally uses the recommendations of the standard B31G [11] where the yield stress in the presence of corrosion σ_f is calculated as follows:

$$\sigma_f=\frac{[\sigma](1-X)}{1-\frac{X}{M}} \tag{12}$$

where:

$[\sigma]$, specified minimum yield strength,

M , Folias factor

with:

$$X=\frac{A}{A_0}=\frac{d}{t} \tag{13}$$

and:

$$M=1+\sqrt{0,4\left(\frac{2C}{\sqrt{Rt}}\right)^2} \tag{14}$$

where:

A , area of the missing metal,

A_0 , original cross-sectional area,

d , depth of metal loss,

t , nominal wall thickness,

$2C$, length ($L = 2C$),

R , radius of pipeline.

If one neglects the influence of the corrosion length and that one considers that the principal dimension characterizing the failure risk is represented by the corrosion depth then, while rearranging the relation (12) it comes:

$$d_R = t\left(\frac{[\sigma] - \sigma_f}{[\sigma] - M^{-1}\sigma_f}\right) \tag{15}$$

As the evolution depth of corrosion with time is a random variable, the probability of failure is then defined by the integral (figure 4):

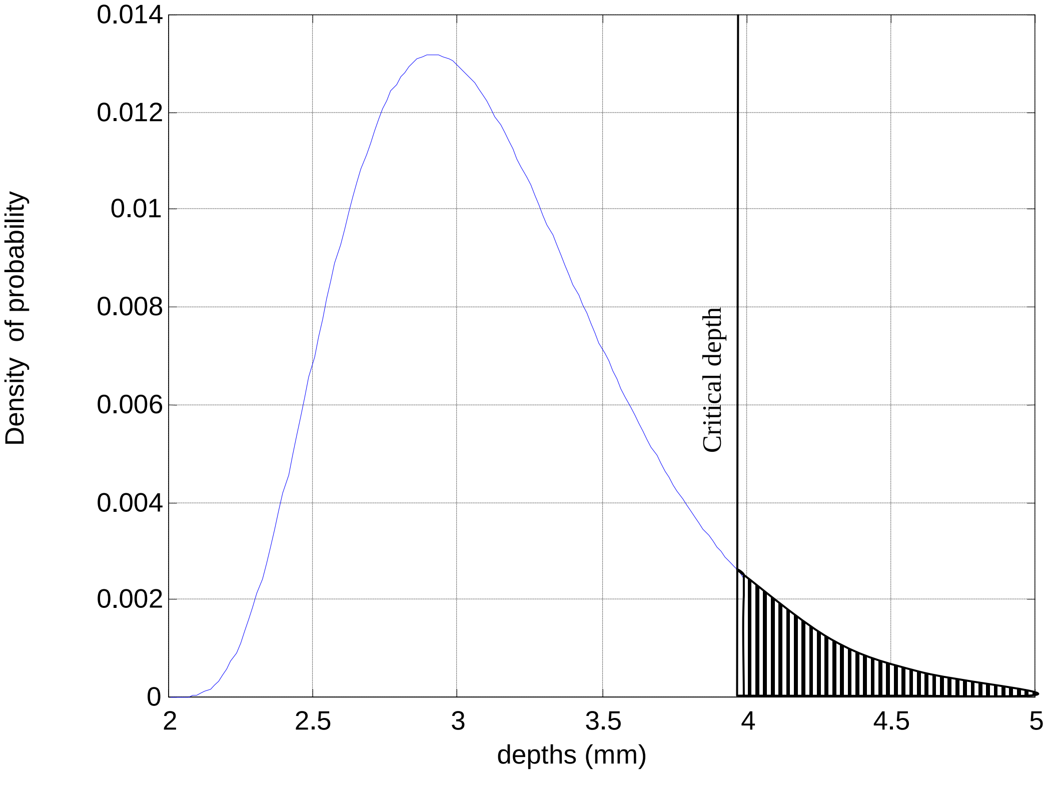

Fig 4 : Probability of failure of a corrosion point

$$P_R = \int_{d_R}^{t} f(d)dd = F(t) - F(d_R) = 1 - F(d_R) \tag{16}$$

finally the probability of pipeline will be expressed as follows :

$$P_{R\_PIPE} = \sum_{i=1}^{n} P_{Ri} \quad (17)$$

CONCLUSION

Internal and external corrosion affects many installations in industry, this phenomenon constitutes our days a significant problem to solve or at least envisage its evolution in time in order to avoid any sudden failure. The significant progress recorded in the field of the inline diagnosis, mainly in the design of tools knows as "intelligent, allows at the present time the detection and the localization of practically all the defects of internal and external corrosions. However, the inline diagnosis operations present the disadvantage of being excessively expensive, from where the importance to grant to rigorous planning of these operations. The inline diagnosis represents a recent technology which explains why the pipelines currently in exploitation all over the world have not undergone does not undergo more than two inspection, most often having been inspected only one time during their exploitation. Which makes the accumulated information very reduced. The forecast of the corrosion evolution in time for the pipelines having undergone a single inspection becomes very delicate. In this article we presented an approach of resolution of this problem of corrosion speed assessment while being based on a probabilistic model which is the Bayesian inference. This technique makes somewhat possible to capitalize the available information presented in the form of interval giving an estimation a priori of corrosion speed. Then to correct this information by the data resulting from our own diagnosis in order to adapt it to our context. Consequently the corrosion speed estimation a posteriori will reflect the particularity of the pipeline to diagnose and will make possible to envisage the evolution of the anomalies in time and to foresee a planning of the interventions allowing a repairing of the installation.

This approach can assist pipeline operators in defining the future integrity management strategy and in maintaining the integrity of their gas pipelines while optimizing In Line inspection intervals, resulting in cost-effective pipeline integrity management.

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