

SAMPLING AND RISK ASSESMENT METHOD FOR METALLURGICAL INSPECTION OF PIPES AND TANKS

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Abstract: This paper gives a general overview of a method developed to optimised NDT inspection planning and results analysis. This computerized tool offers sample size calculation, statistical analysis of thickness measurements and life prediction modules. In each step and module, calculations are driven by equations developed using data gathered from previous expertise and laboratory work. The equations are updated when new case studies are added to the system data base. The method was initially developed for radiographic and ultrasonic inspection of corroded pipes. It can be described in eight steps: 1) Assessment of degradation severity 2) Determination of inspection method 3) Initial sample size calculation 4) Field testing 5) Results analysis 6) Probability and reliability calculations 7) Predictions and degradation pattern 8) Results presentation. Steps 4 to 7 can be recomputed to get a better confidence index. Calculation and results presentation are customized based on a questionnaire filled by the project engineer.

Introduction: Metallurgical, chemical, petrochemical, energetic and marine industries are using different types of pipes and tanks to carry and stock gaseous, liquid and solid products. These pipes and tanks are subjected to internal and external degradation caused by erosion and corrosion. For certain types of installation like pressurized tanks and pipelines, there exists regulation about inspection frequencies and minimum acceptable wall thickness [1-4]. In other cases, degradation control and inspection parameters are left to the goodwill of the installation's owner.

Non-destructive techniques (NDT) such as radiography (RT), ultrasound (UT) and Eddy current (ET) are widely spread inspection methods used to monitor pipes and tanks degradation [2,3]. They all give information about wall thickness and about the existence of metallurgical flaws. However, inspection is never full proof. Generally, the installations are inspected partially and the methods have limitations. Since corrosion and erosion of metals are rarely uniform, there exists a risk associated with recommendations and predictions based on partial inspections. This risk is related to sampling size, corrosion mode and inspection method.

The objective of this paper is to give an overlook on the corrosion expert system developed by X-per-X inc. research group. This fully computerized diagnostic tool has been designed to fulfil two needs of the company's NDT group. The system optimises sampling according to the corrosion severity and a needed confidence level. It also calculates the probability of failure a number of years subsequently to inspection. This paper is divided in three sections. Section 1 gives an overview of the system's philosophy. Section 2 details the steps and calculations leading to a preliminary sample size. A description of the method used to analyse the inspection data is given in section 3. Finally, section 4 is a summary of the type of predictions and results presentation offered by the system.

System overview: To design the system, the initial train of thoughts was decomposed in nine steps regrouped in three modules (Fig. 1).

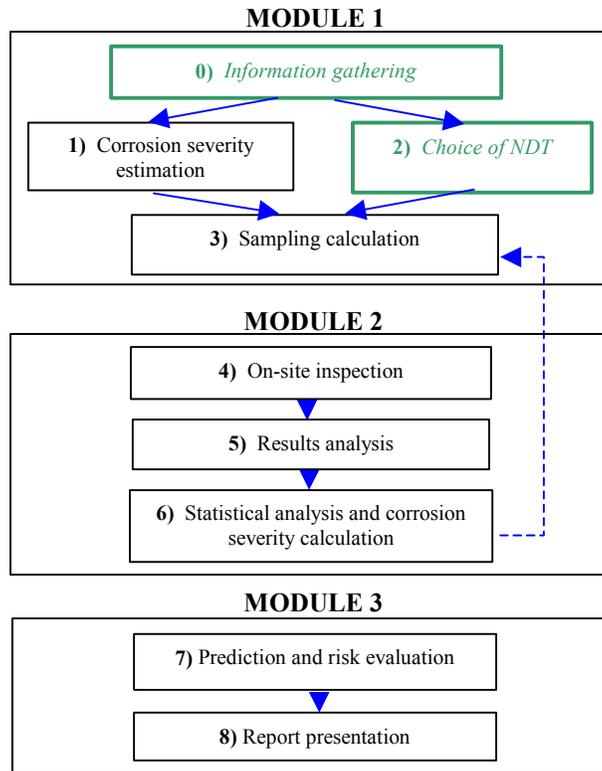


Fig. 1. Nine steps describing the system method

First of all, it was asked to the NDT group how they choose the inspection method and sample size for a particular application. This first question led to the definition of the corrosion severity factor (step 1). To estimate this factor, preliminary information about the infrastructure's characteristics and history needed to be gathered (step 0). This step is not included in the software since it necessitates an interaction between the project engineer and the client.

From the estimation of the severity factor, an equation leading to a preliminary sample size was created (step 2). Sample size calculations had the objective of minimizing the inspection area for a given confidence level. Discussions with clients and engineers quickly led to the conclusion that a severe corrosion situation needed a higher confidence level. From that point on, the confidence level from which sample size is calculated was linked to the corrosion severity factor.

Calculations in module 1 are based on a corrosion severity factor estimated from the questionnaire's parameters. In module 2, the real corrosion severity factor is calculated from the inspection results and analysis. The sample size is recomputed and compared to the preliminary sample size of module 1. If the actual corrosion severity factor is higher than the estimated one, more areas must be inspected. Once the confidence level is respected, predictions are made about residual life and inspection frequency (module 3). Part of the information gathered is wrapped up in an interactive report sent to the client.

Preliminary calculations (steps 0 to 3): The engineer in charge of the inspection project generally accomplishes the first step. For each new installation, information must be collected to feed the system. The questionnaire proposed in Fig. 2 was built to answer the needs of X-per-X inc.'s projects. It was inspired from risk management methods used for pipelines [4].

1. Project and Client Information

Project Number :	
Company :	
Address:	
Phone number:	
Contact:	

2. Installation Initial Information

Type of installation:	
Regulations or Code:	
Material:	
Nominal thickness:	
Corrosion allowance:	
Nominal diameter:	
Over all length:	
Joining:	
<ul style="list-style-type: none"> • Mechanical • Welding • Dissimilar metals 	
Cathodic protection:	
Anodic protection:	

3. Installation Actual Information

Age of the installation:	
Signs of external corrosion:	
Signs of internal corrosion:	
Leakage or reparations:	
<ul style="list-style-type: none"> • Number • Last occurrence 	
Last corrosion inspection:	
Cleaning or purging:	
<ul style="list-style-type: none"> • Cleaning product • Last occurrence 	

4. Internal corrosion

Type of product flowing:	
Maximal pressure:	
Maximal operation temperature:	
PH range:	
Product level or pipe efficiency:	
Oxygen concentration:	
Internal coating or inhibitor :	

5. External corrosion

Type of environment:	
Coating or protection:	
Surface profile:	

Fig. 2. Questionnaire used in step 0

Any relevant information, which characterizes an installation and its environment, could be added. The information gathered is entered in the system database for future use and reference. Usually, the same installation will be inspected more than once over its lifetime.

Using the information gathered from step 0, the system calculates 26 factors that characterize the corrosion behaviour. The parameters are classified in three categories: Corrosion Thermodynamic, Corrosion Kinetic and Others. To quantify the corrosion behaviour of an installation, a corrosion severity factor has been defined. This factor can be calculated using thickness measurements, or estimated by a semi-quantitative relation from preliminary information. The calculated severity factor is called α and the estimated one is α' . The estimated severity factor, α' , is aimed to guide the initial sampling size and measurement intervals. To elaborate the semi-quantitative relation that gives the estimated corrosion severity factor (α'), screening experiments have been performed. At this stage, the model includes 8 parameters out of 26. A second phase of experimentation has been started to confirm or revise the relation. Figure 3 shows an example the system's interface used for Module 1.

Step 2 is not computer assisted and can be completed before or after step 1. It consists in choosing the most appropriate non-destructive technique. The choice of NDT usually depends on the accessibility and shape of the installation. For example, ultrasound may be favoured to evaluate reservoir floor thickness. In the same state of mind, radiography may be used when inspecting pipe systems containing welds, valves and outer surface defects. Finally, the Eddy current technique is proposed by the ASME for examination of non-ferromagnetic heat exchanger tubing. Usually, the project engineer and the installation's owner take the decision. Once the inspection method has been chosen, the testing parameters must be entered in the method file. Parameters for RT would be the following: source-to-object distance, source diameter, source isotope or X-ray voltage-amperage, film sensitivity, film type, etc... For UT inspections, parameters are: probe diameter, surface condition, couplant, angles, frequency, measurements spacing. Using this information, the technique precision (Δe) and sensitivity (Δx) are automatically calculated. The equations used to calculate these parameters have been developed from laboratory tests done with X-per-X inc.'s non-destructive equipments in different conditions. The precision factor is applied to thickness measurements and the sensitivity to the observations' position. The precision will affect the upper and lower thickness boundaries (step 6) and the sensitivity will affect the measurement intervals.

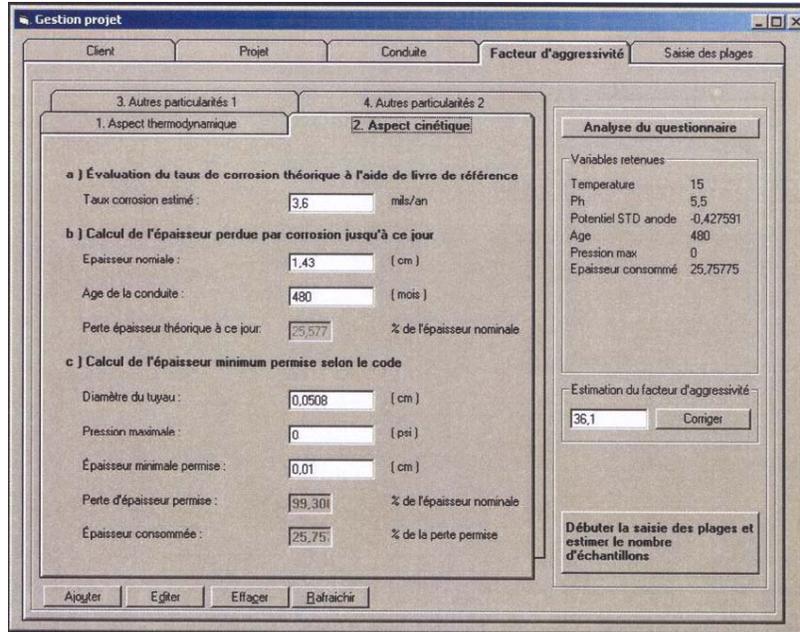


Fig. 3. Module 1, Step 1 system's interface

Step 3 was created to facilitate inspection planning. Sample size and distribution are proposed according to the installation design, the corrosion severity factor and the inspection method characteristics. The installation is first divided in lots, which are susceptible to develop different corrosion patterns. For example, horizontal pipes, vertical pipes and elbows are part of different lots. To calculate the number of samples needed from each lot, it is assumed that thickness measurements will follow a normal distribution law. For a fixed lower thickness limit, e_L , the number of samples, n , needed to attain a targeted probability level, P , is given by the following equation:

$$n = 4z^2 \sigma^2 \div R^2 \quad \text{equation (1)}$$

with z being the value of the standard normal deviate for a given probability level P ; σ is the standard deviation of the thickness population; R is the width of the confidence interval which can be expressed as:

$$R = 2 (e_{av} - e_L) \quad \text{equation(2)}$$

When it is possible to take a preliminary shot or do few ultrasonic measurements, the average thickness, e_{av} , and the standard deviation, σ , are calculated from those results. If no preliminary results are available, an estimation of e_{av} and σ is done based on similar corrosion cases. For each project, the corrosion severity factor, the average corrosion rate and the standard deviation of measurements are stored in a general database. This information is used to refine corrosion severity equation and sample size estimation.

The probability level needed, P , is related to corrosion severity factor or can be adjusted to specific needs. When corrosion is severe, in other words out of control or near the minimum allowed thickness, a higher probability level will be use. The lower confidence limit, e_L , is generally related to a thickness value which will give a residual life of one year. This thickness value is estimated using a theoretical corrosion rate, t_{th} , and the minimum allowed thickness, e_{min} . The method precision, Δe , is added to the calculated value:

$$e_L = e_{min} + t_{th} * I yr + \Delta e \quad \text{equation (3)}$$

In table 1, three examples of sample size calculation are given.

Table 1 Initial sample size calculation and parameters

α' or α	$e_L ; R$ (mm)	σ (mm)	$P ; z$ %	N
10	2 ; 16	1	80 ; 1.28	1
50	5 ; 10	5	90 ; 1.64	3
90	9 ; 2	1	99 ; 2.58	7
10	2 ; 16	1	80 ; 1.28	1

One may notice that the number of samples is proportional to the installation corrosion severity factor. High corrosion severity factor is obtained for a high corrosion rate, which increase the e_L value, and enlarge the band of thickness variation, affecting σ .

Testing and Analysis (steps 4 to 7): Step 4 is the On-site inspections. It must be done as closely as possible to the parameters specified in step 2. If modifications are needed, it is possible to enter the new parameters in an interactive window. Following inspections, X-ray films are digitalized using a scanner and ultrasound data is downloaded, filtered and displayed on the screen (Fig. 4).

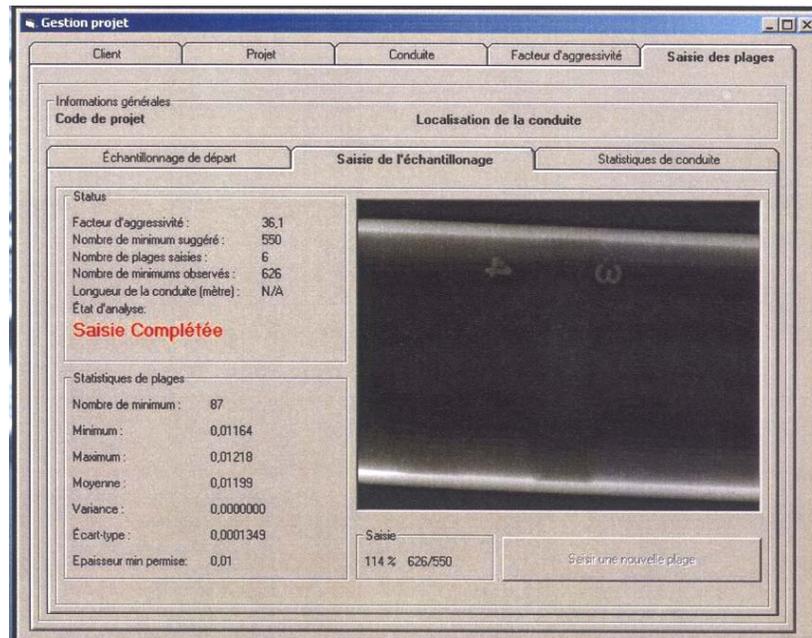


Fig. 4 Radiographic film of a corroded pipe

Step 5 was developed to automatically extract thickness measurements from pipes tangential radiographs. Image analysis and form recognition is applied to detect the pipe inner and outer walls. Thickness are measured perpendicular to a reference line which represents the pipe contour. These measurements give the thickness distribution of a sample and are used to calculate e_{av} and σ (Fig. 5). The minimum wall thickness of a sample, s_{min} , is also computed using specific algorithms. Finally the corrosion rate distribution is calculated for each observation based on the nominal thickness and the installation age.

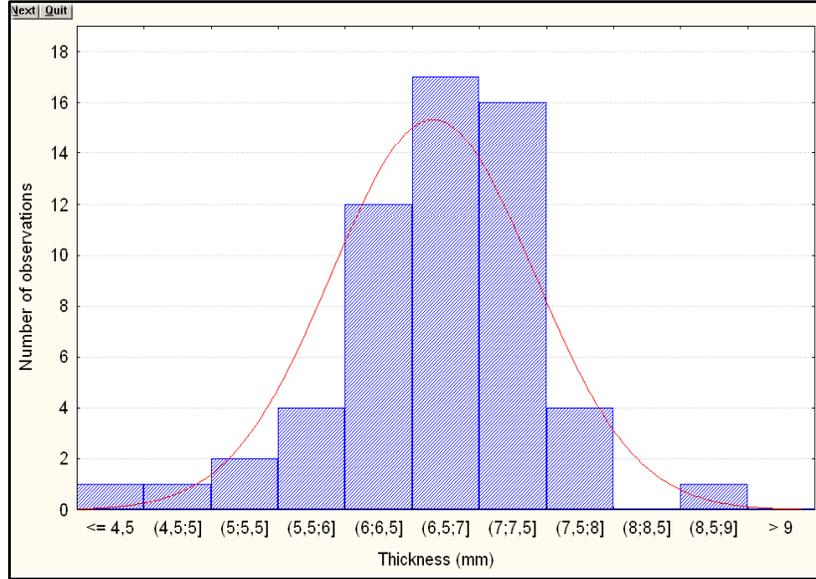


Fig. 5 Thickness distribution of a pipe wall

Step 6 consists in the calculation of the real severity factor. This value is the heart of the expert-system. It dictates the sample size and the probability level. It has been studied for many cases and it was observed that three corrosion parameters affect it significantly. These three parameters are the remaining useful life, the corrosion mode and the corrosion's kinetic. The most important factor is the remaining useful life, t , which is estimated using the lower confidence limit, e_L , and the average corrosion rate. The average corrosion rate, $(de/dt)_{av}$, is given by results analysis explained in step 5. The remaining useful life is then classified as proposed in table 2 and corrosion severity coefficient β , is attributed to each class.

Table 2 Remaining useful life

Classification	Severity, β
$\text{Min}(t_0) \leq t < \text{Max}(t_0)$	1
$\text{Max}(0.75 t_0) \leq t < \text{Min}(t_0)$	2
$\text{Max}(0.50 t_0) \leq t < \text{Max}(0.75 t_0)$	4
$\text{Max}(0.25 t_0) \leq t < \text{Max}(0.50 t_0)$	6
$\Delta e \div (de/dt)_{av} \leq t < \text{Max}(0.25 t_0)$	8
$t < \Delta e / (de/dt)_{av}$	10

Where t_o is the initial life time of the installation based on the nominal wall thickness and the calculated average corrosion rate. In table 2, the minimum and maximum boundaries of the remaining useful life are calculated based on the thickness error introduced during measurements:

$$\text{Max}(t) = (e_{av} - e_{min} + 2\Delta e) \div (de/dt)_{av} \quad \text{equation (4)}$$

$$\text{Min}(t) = (e_{av} - e_{min} - 2\Delta e) \div (de/dt)_{av} \quad \text{equation (5)}$$

The corrosion mode of the system is identified according to the thickness measurements' distribution. First of all, a pitting factor, which will identify a thickness depression as a pit, must be determined. For radiographic analysis, the ASTM G46 standard states that pits must be deeper than 0.5% of the metal thickness to be detected. This criteria can be express as:

$$e_{pit} \leq e_{av} - 0.005 e_{av} \quad \text{equation (6)}$$

Other criteria have also been used.

Once a thickness measurement is identified as a pit, the extent of pitting is evaluated. This can be quantified by the ratio of surface occupied by pits versus the total inspected surface. To be categorized as general corrosion, a criteria on the sample minimum thickness, s_{min} , is also added. Actually, the corrosion modes are divided in five categories according to the boundaries proposed in table 3. A corrosion severity coefficient, χ , is attributed to each class.

Table 3 Classification of corrosion mode

Criteria	Corrosion mode	Severity, χ
$0\% \leq P(e_{pi}) < 20\%$	General if $s_{min} > (e_{av} - 2\Delta_e)$	1
$0\% \leq P(e_{pi}) < 20\%$	Pitting 1 if $s_{min} < (e_{av} - 2\Delta_e)$	3.0
$20\% \leq P(e_{pi}) < 40\%$	Pitting 2	2.5
$40\% \leq P(e_{pi}) < 60\%$	General Pitting	2.0
$60\% \leq P(e_{pi}) < 80\%$	Localized	1.5
$80\% \leq P(e_{pi}) < 100\%$	Insufficient data	Insufficient data

The third part of the results analysis consists in evaluating the kinetic of corrosion. This is relevant only if multiple inspections have been conducted over a period of time. The initial corrosion rate is calculated knowing the system age and the pipe or reservoir nominal thickness. For subsequent inspection, an average corrosion rate is calculated based on the average thickness measurements and the year of inspection. The evolution of the corrosion rate as a function of time is plotted and categorized. In the latest system version, the following categories have been used: logarithmic, parabolic, linear or exponential. Each category is qualified by a corrosion severity coefficient δ . Finally, the corrosion severity factor which characterizes the system is calculated using the following relation:

$$\alpha = \beta^2 \chi \delta \quad \text{equation (7)}$$

The sample size, n , is then recomputed as in step 3 using this value, the average corrosion rate, the standard deviation and the average thickness calculated in step 5. If the sample size is bigger than the initial one based on the estimated corrosion severity factor, more areas must be inspected.

Prediction and presentation (steps 7 to 9): The prediction and risk evaluation can be customized to client needs. Some installation owners will want to know the remaining useful life to a targeted confidence level. Others will prefer to know the location of the thinnest area to schedule repairs. An interactive window is also available to calculate the probability of getting a targeted thickness base on EVS (extreme value statistic) analysis of samples' minimum thickness. For NDT purposes, the prediction module serves to schedule the next inspection. When a history of inspection exists, the inspection plan is based on the evolution of a with time or on a targeted thickness. We are also developing custom corrosion models for some companies interested in monitoring closely the corrosion behaviour of their installations.

The presentation module creates an interactive report of the inspection and evaluation which is usually recorded on a CD. Details about probabilistic analysis and equations do not figure. The main window shows a general view of the installation on which the inspected areas have been pin marked (see Fig. 6). It is possible to click on a pin to view the X-ray or ultrasound image. Information about the thickness measurements, the corrosion severity factor, the corrosion mode and the corrosion kinetic are displayed below the plot.

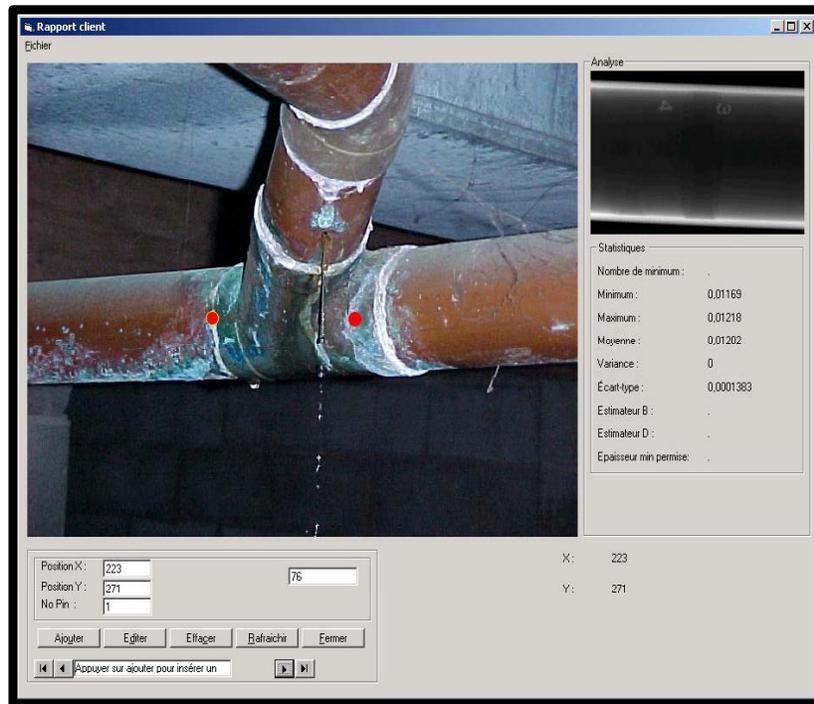


Fig. 6 Step 8 main window

Conclusions: The overall thinking behind the system is simple but a lot of information and case history are needed to get good results. This system was built for three major reasons. First of all, it is a way to offer the client a better follow up of his infrastructure inspection. Custom made equations are developed for specific clients based on their inspection history. Secondly, new clients will get knowledge from similar cases through the expression of the corrosion severity factor and the sampling equation. This will optimise the inspection costs and insure a high confidence in results. Finally, the information collected and its objectivity is maximised through automatic measurements and statistical analysis.

X-per-X inc. is constantly working with its clients on the development of this expert-system. Bench testing are in progress at École Polytechnique of Montreal to refine the equations behind the corrosion severity factor and the sampling size. A partnership has been proposed to finance a five year research program which will serve to the development of prediction models specific to our client's installations. Part of the work will also be aimed toward the creation of an interactive website where client will be able to consult their file and schedule new inspection from their work place.

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