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Monitoring Corrosion Defects in Oil Pipelines

مراقبة عيوب النخر في خطوط أنابيب البترول

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KEYWORDS:
Pipeline; Corrosion defects; Control chart; Test of hypothesis; Risk; Integrity

الملخص العربي:-إن خطوط الأنابيب تمثل استثماراً ضخماً لشركات البترول، ولذلك فإن الإخفاقات الناتجة عن النخر تمثل ضغطاً اقتصاديا آخر بمركبات تكلفة متعددة وخاصة تكلفتي الإصلاح وانخفاض سعة النقل. ويمثل النخر سبباً متنامياً لإخفاق خطوط الأنابيب المتقادمة. ولذلك فإن تحليل النخر يعتبر عملية حيوية لإدارة سلامة الخطوط. وهذا البحث يقدم روتين مبسط لمراقبة عيوب النخر في خطوط الأنابيب باستخدام خرائط الجودة وبعض التحليلات الإحصائية البسيطة، وهو ما تم استعراضه اعتماداً على حالة دراسية فعلية وبدراسة معيار الحجم الأقصى للنخر. ويمكن استخدام مقاييس أخرى لاستخراج استنتاجات مساعدة. وهذا الروتين من شأنه تمكين مسئولي الصيانة من التعرف على معولية خطوط الأنابيب والتعديل الفعال لخطط التفتيش والصيانة لما تبقى من عمر الخطوط

***Abstract*—Pipelines represent a large capital cost for oil organizations. Therefore, corrosion failures have significant economic impact with several cost components, particularly repair and loss of transportation capacity. Corrosion is a growing cause of failures in aged pipelines. Thus, corrosion analysis is a vital task for the management of pipeline integrity. This paper presents a simple routine to monitor the corrosion defects in pipelines based on control charts and simple statistical analysis. A real life case is studied based on maximum corrosion volume (MCV). Other dimensions can be adopted to make auxiliary conclusions. This routine enables maintenance personnel to predict the reliability of pipelines and effectively modify inspection and maintenance plans for next part of pipeline life.**

I. INTRODUCTION

Pipeline integrity management refers to all efforts such as design, construction, operation, maintenance, etc. that ensure continuing pipeline integrity (Cosham et al. 2007). Review pipeline integrity management in Kishawy and Gabbar (2010).

Aging is the main problem that affect the integrity of high-pressure transmission pipelines. Historically, several disasters have been occurred due to pipeline degradation in some organizations (Hu et al. 2014). Corrosion defects represent a significant shock on lifetime of high-pressure pipeline networks. Therefore, such defects constitute a very critical source of failure in pipeline networks, which can pose potential threats to humans, environment, and investment (Amirat et al. 2006; Meresht et al. 2011).

Since the corrosion is the degradation of a material through environmental interaction, it may occur due to several factors such as unsuccessful protection, coating failure, soil, air, surrounding water, interfacial deboning, inhibitor failure, etc. (Peabody 2001; Dawotola et al. 2009). In turn, several types of corrosion occur internally and externally on pipelines (see Alkazraji 2008; Dawotola et al. 2009). Therefore, corrosion defects become necessarily taken in consideration in both design and operating stages for both internal and external corrosion.

Analysis of corrosion defects is recognized as an essential tool for decision making in pipeline integrity management (for instance, see Hong 1999; Cosham et al. 2007; Teixeira et al. 2008; Amirat et al. 2009). Generally, various methodologies were introduced to analyze the risk of corrosion defects in pipelines with different models. Probabilistic models are more effective because of involving the nature of the degradation process. These models require substantial large amounts of data. This paper interest is the analysis of corrosion defects based only on corrosion geometry to monitor and assess risks

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to pipeline integrity using a quality method. Other parameters of corrosion defect aren't explicit in the analysis but they can be predicted implicitly. This direction seems to be hidden in the literature. However, some existing methodologies will be mentioned as nearly related to this work.

Probabilistic models for corrosion defect growth in pipelines are involved in two categories—random variable-based and stochastic process-based. The latter category is found more realistic and advantageous because it can take into account the temporal variability of the degradation process. The former category can be used effectively as a base for process modeling in the second category. For more discussion, refer to Amirat et al. (2006), Teixeira et al. (2008), Zhou (2010), Bertuccio and Moraleda (2012), Zhang and Zhou (2013), and Gomes and Beck (2013). Therefore, the probability distribution of corrosion dimensions and corrosion growth rate received attention in the analysis of corrosion defects of pipelines such as Caleyo et al. (2009a), Ren et al. (2012), and Valor et al. (2013). Also, the lifetime of cracked corroded pipelines with crack growth rate were studied such as Hu et al. (2014).

Teixeira et al. (2008), based on simulation and finite element, assessed the reliability of pipelines with corrosion defects using the first order reliability method. They compared their results with those obtained from practical codes. Caleyo et al. (2009b) introduced a predictive corrosion growth model based on experimental data to describe the time evolution of corrosion depth. Zhou (2010) introduced a stochastic methodology based on simulation to evaluate the time-dependent system reliability of a pipeline segment with multiple active corrosion defects and internal pressure loading. He considered the pipeline segment as series system differentiating three failure modes. This work is continued in Zhang and Zhou (2013) to include in-line inspection. Gomes and Beck (2013) combined the models of Zhou (2010) and Caleyo et al. (2009b) to optimize inspection planning of corroded pipelines based on simulation. Bertuccio and Moraleda (2012), based on fuzzy logic, presented a methodology to assess the risk of corrosion in pipelines. They proposed the combination of fuzzy logic and expert judgment for probability modeling and assessing the severity of defects.

In summary, the methodologies developed to assess the reliability of corroded pipelines especially for external corrosion provided much effort in addressing the factors such as uncertainties of defect dimensions and failure model used (Valor et al. 2013). It is found less attention was given to the probabilistic distribution of corrosion rates, which determines the time evolution of the pipeline reliability over the period of interest. Valor et al. (2013), based on different corrosion rates from the National Association of Corrosion Engineers (NACE) and simulation, developed a framework to assess the reliability of corroded pipelines. Valor et al., with application to repeated in-line inspection data, showed that the best distribution of corrosion rate is that considers the ages and sizes of the corrosion defects as well as the observed dependence of the corrosion defect depth on time. These findings are necessary for the current work because the analysis is mainly based on the change of corrosion volume over pipeline length and age.

The main objective of this paper is to simplify the task of corrosion defect analysis of pipeline systems based on quality tools with minimum number of corrosion parameters. A supplement objective is to introduce a guidance framework for proposing a variety of corrosion analysis methods. The rest of this paper is organized as follows. An industrial case of pipelines is described in §2. The proposed methodology is introduced in §3. Results and discussions are demonstrated in §4. Conclusions and recommendations are given in §5

II. CASE DESCRIPTION

An oil transportation company collects the data of corrosion defects through a popular inspection method, Magnetic Flux Leakage smart pig. This pig is actuated with inspection gauges which detect and locate corrosion defects on both internal and external surfaces while the data are transferred to a computational interface. The pig is moved internally along the pipelines. The data are recorded for thousands of kilometers. A corrosion defect dimensions length, width and depth are registered. A research sample of buried pipelines is taken such that it accommodates three different types of soil one kilometer each, and two years inspection. Thus, the analysis comprises six samples symbolized as S106, S206, S306, S111, S211, and S311; where S refers to soil. The case is summarized as:

Type	**Longitudinally welded pipes transport oil**
Material	Carbon steel API 5LX60
Diameter	42 inch
Wall thickness	22.22 mm to 9.5 mm
Length	320 km
Installation year	1976
IP Inspection years	2006, 2011 (inspection/maintenance schedule is every five years)
Defect	Corrosion
Soil 1 (Specimen 1)	Sandy with small rocks soil; pipes with operating pressure 30 bars
Soil 2 (Specimen 2)	Rock soil; pipes with operating pressure 15 bars
Soil 3 (Specimen 3)	Clay soil; pipes with operating pressure 30 bars

III. METHODOLOGY

The proposed methodology for analyzing corrosion defects of pipelines is applied here based on MCV of each defect; this variable is selected after extensive study of literature. Each dimension can be analyzed separately. In addition, other variables can be manipulated in the same way. Since the dimensions of corrosion defect are random variables, the corrosion volume is dealt as a function of random variables and its probability distribution is examined. The analysis consists of three components: (1) descriptive statistics, (2) test of hypothesis, and (3) control charts. Mainly, Shewart control charts are demonstrated as a practice for monitoring the risk of corrosion defects in pipelines. Therefore, the defect data along each pipeline segment should be grouped in samples of a proper size (for instance five points). Thus, the distance becomes in replace of time that used in conventional application of control charts. The results can be used to improve the reliability of pipelines through modifying inspection and maintenance plans. The proposed methodology has no restrictions on the form of probability distributions of defect geometry or defect growth rates. This methodology will be described through the selected industrial case study.”

IV. IMPLEMENTATION

In this section, the proposed methodology is conducted to the selected industrial case study. The MCVs (corrosion length in mm × corrosion width in mm × corrosion depth to pipe wall thickness ratio) are calculated for the corrosion defects of sampled specimens. The results are registered and discussed as follows:

4-1.Descriptive statistics and test of hypotheses

Several descriptive statistics including graphs are completed for MCV of the case study. Table 1 shows the most representative part of descriptive statistics. It primarily describes (a) corrosion growth with time, and (b) effect of soil change on the MCV. It reveals the next findings

1. In general, mean MCV is about 10 mm3/mm. Mean external MCV is about 4.5 times greater than mean internal MCV.
2. Mean corrosion growth rate is about 57%.
3. Mean internal corrosion growth rate is about 85%.
4. Mean external corrosion growth rate is about 31%.
5. In general, mean CV of MCV is about 1.5, while mean CV of internal MCV is 2.97 and mean CV of external MCV is 1.30. For each year, mean internal CV is lower than mean external CV, except year 2011 for soil 3. For each soil, mean internal CV is lower than mean external CV, except soil 3.
6. Each soil recorded a high external corrosion growth rate. Internal corrosion growth rate is high for soil 2 and soil 3. Soil 3 recorded unexplainable very high internal MCV (19,382) for year 2011

TABLE 1

. DESCRIPTIVE STATISTICS FOR MCV OF THE CASE

Soil	Year	Surface	Mean	StDev	N	CV
(1)	2006	INT	1,534	882	146	0.57
		EXT	10,065	13,725	171	1.36
		TOTAL	6,136	10,947	317	1.78
	2011	INT	1,694	728	92	0.43
		EXT	13,381	16,639	189	1.24
		TOTAL	9,555	14,705	281	1.54
	TOTAL	INT	1,596	828	238	0.52
		EXT	11,806	15,393	360	1.30
		TOTAL	7,743	12,953	598	1.67
(2)	2006	INT	2,972	3,267	31	1.10
		EXT	9,447	10,776	175	1.14
		TOTAL	8,473	10,271	206	1.21
	2011	INT	4,374	4,289	9	0.98
		EXT	12,671	17,188	441	1.36
		TOTAL	12,505	17,064	450	1.36
	TOTAL	INT	3,287	3,512	40	1.07
		EXT	11,755	15,695	616	1.34
		TOTAL	11,239	15,366	656	1.37
(3)	2006	INT	2,897	3,038	54	1.05
		EXT	10,251	16,458	193	1.61
		TOTAL	8,643	14,922	247	1.73
	2011	INT	19,382	38,096	12	1.97
		EXT	13,359	13,149	231	0.98
		TOTAL	13,657	15,231	243	1.12
	TOTAL	INT	5,894	17,152	66	2.91
		EXT	11,944	14,811	424	1.24
		TOTAL	11,130	15,268	490	1.37
TOTAL	2006	INT	2,046	2,112	231	1.03
		EXT	9,931	13,923	539	1.40
		TOTAL	7,565	12,249	770	1.62
	2011	INT	3,786	13,190	113	3.48
		EXT	13,012	16,063	861	1.23
		TOTAL	11,941	16,026	974	1.34
	TOTAL	INT	2,617	7,776	344	2.97
		EXT	11,826	15,343	1400	1.30
		INT	10,009	2,112	231	1.03

MCV: maximum corrosion volume (mm3 per mm of pipe wall thickness); INT: internal; EXT: external; CV: coefficient of variation

These findings primarily proved that the corrosion growth rate is high for both, internal corrosion and external corrosion. This can be explained by the age of pipes in addition to the large time length between maintenance works. Thus, it can be said that the pipes become in wear out period of the bathtub curve of reliability. This is confirmed by the high variability of MCV which is explained by high CVs. Generally, irrespective to soil type, external MCV is significantly larger than internal MCV even the internal corrosion growth is larger. This is the condition for each soil and each year except soil 3 for year 2011 (there is a big trouble at this portion of pipes; inspection and maintenance processes should be reviewed). Furthermore, it strongly seems that the corrosion process isn’t homogeneous as seen simply from Fig. 1, and the internal maintenance process is poorer than that external. Therefore, it can be concluded that the corrosion growth rate is very high and the lines need to serious decisions about inspection/repair/replacement. These results are confirmed using sensitivity analysis of test of hypothesis ANOVA LSD. (Notice that many tests of hypotheses are carried out and all confirmed these conclusions with zero p-value.)

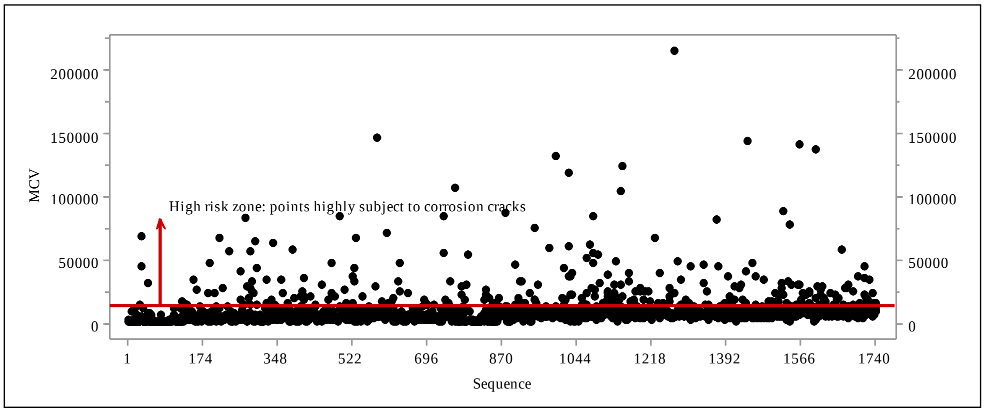


Fig. 1 Sequence plot for MCV of the case study

It is found that location change and time change both have some effect on internal MCV while specimen 1 records lower internal MCV. For year 2006, ANOVA LSD with zero p-value confirms that internal MCV of specimen 1 is significantly lower than that of specimen 2 and specimen 3, approximately by mean (1,437; 1,363). For year 2011, ANOVA LSD with zero p-value confirms that internal MCV of specimen 1 is significantly lower than that of specimen 3, approximately by mean 17,688; and specimen 2 with 0.006 P-value is significantly lower than that of specimen 3, approximately by mean 15,008. Thus, specimen 1 can be confirmed as better and specimen 3 can be confirmed as worst related to internal corrosion. (Notice that all three specimens are identical in material, diameters, operating conditions, and protection method.)

Intuitively, soil type may affect the external corrosion events. In general, soil change has some effect on external MCV while specimen 2 records lower external MCV. Nevertheless, ANOVA LSD doesn’t confirm significant difference in external MCV between any pair of the three specimens for each year. However, specimen 2 displays lower external corrosion. This can be interpreted by the degree of homogeneity in protection processes of external surfaces of pipes or by the homogeneity of soil effect or both. Irrespective to specimens, external MCV of year 2011 is significantly higher than that of year 2006 (t-test with 0.006 p-value) and year 2011 yields the same for internal MCV and for overall MCV.

Fig. 2 represents the Classification and Regression Tree (CRT) method for the case study. This statistical classification tree gives an overview and additional clarity for the results of this section. It is based on ANOVA test of hypothesis and recommended here as an auxiliary tool for analysis and decision making in pipeline integrity management.

Furthermore, probability distributions of corrosion dimensions and their growth rate in pipelines, specially aging buried pipelines, should be investigated. These distributions are critical to assess the risk of corrosion cracks. In addition, such distributions become essential to develop reliability and risk-based planning models for inspection and maintenance of corroded pipelines (Caleyo et al. 2009a). Localized forms of corrosion are the most serious source of severity that can’t be managed without knowledge of corrosion probability distribution. Most of the current research is found interested in corrosion depth. For further information, refer to Caleyo et al. (2009a) and Velázquez et al. (2014). Here, the probability distribution of MCV is investigated with all variables of the case study. Nearest distribution is found Lognormal for all experiments with medium fit. Fig. 3 shows Three-Parameter Lognormal fit for overall MCV. Notice that the deviation from Lognormality in right terminal of the distribution explains localized corrosion with high risk of cracks. This agrees with the previous results that the inspection and maintenance plans should be reviewed. Finally, the results of this section highlight a principal view about the risk of corrosion defects in pipelines. The MCV is discussed related the case variables individually and entirely that gives an initial picture about the current conditions of pipes and their integrity management

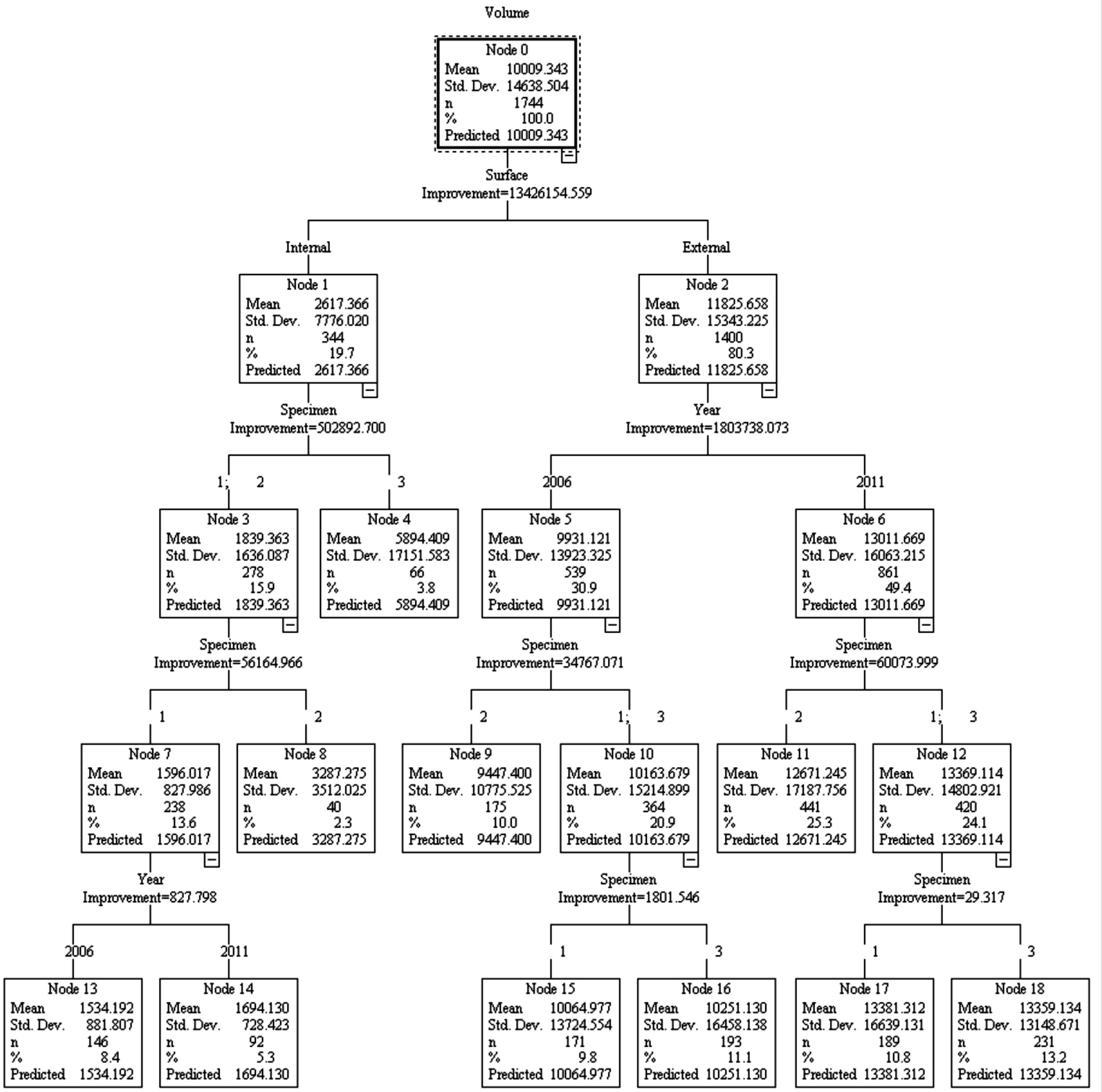
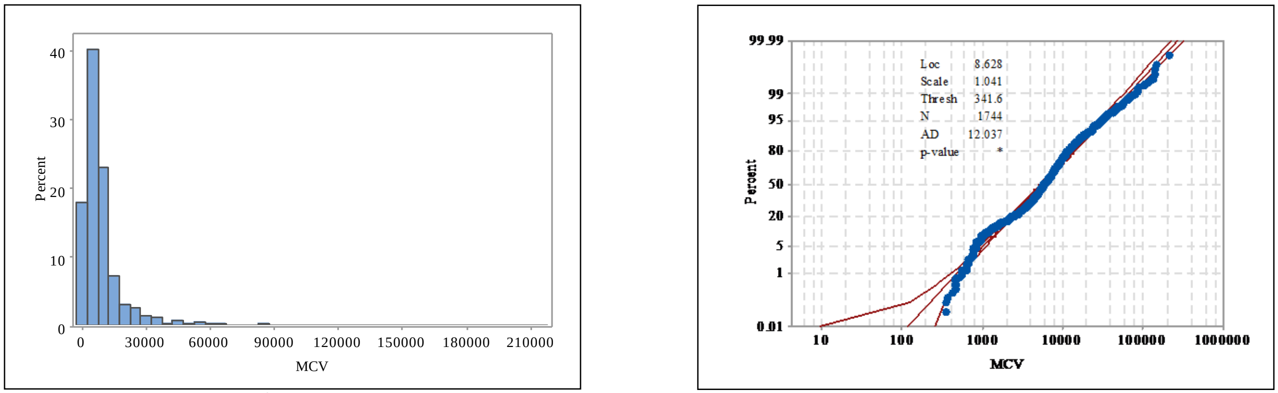


Fig.2. CRT method for the case study variables



(a) Relative frequency distribution

(b) Lognormal probability plot

Fig. 3. Distribution of MCV of the case

4-2. Control charts

Results of §4.1 will be taken in mind in this section to guide a continuous monitoring of the risk of corrosion defects in pipelines using control charts (X-bar/S charts are nominated as major, and X/MR charts as minor). The locations of risk on pipes will appear on the charts that enable to assess, in some way, quantitative/quantitative value for any risk. For instance, risk priority number for a location can be estimated based on samples. Furthermore, the control charts demonstrate the homogeneity of the corrosion process, and delivered inspection and maintenance level (IML).

Intuitively, each chart may contain several patterns; each pattern is formed by several points. Here, points and patterns on control charts will be interpreted slightly different from that in the traditional use of control charts. (Notice that each point represents a region on the pipe surface and each pattern represents larger region or segment.) An out-of-control state inside control limits may indicate process improvement. A continuity of some points around a specific level (inside/outside control limits) may indicate homogeneous corrosion pattern at this segment of pipe. A nonhomogeneous point may be comprised in homogeneous pattern and a nonhomogeneous pattern may include homogeneous points, since the homogeneity is mainly measured by standard deviation. (Review standard interpretation of control charts in Montgomery 2009.)

Each point on X-bar chart and that on S chart will be interpreted as shown in Table 2 and Table 3, respectively. Patterns on X-bar chart will be interpreted as shown in Table 4. The homogeneity of a pattern is judged by the standard deviation of its points on X-bar chart

TABLE 2.
READING X-BAR CHART POINTS.

Point	Severity	IML
$\mathrm{UCL} \le \bar{\mathrm{X}}$	Catastrophic	Ruined
$\bar{\bar{\mathrm{X}}} < \bar{\mathrm{X}} < \mathrm{UCL}$	Very high	Very poor
$\bar{\mathrm{X}} \cong \bar{\bar{\mathrm{X}}}$	High	Poor
$\mathrm{LCL} < \bar{\mathrm{X}} < \bar{\bar{\mathrm{X}}}$	Medium	Good
$\bar{\mathrm{X}} \cong \mathrm{LCL}$	Low	Very good
$\bar{\mathrm{X}} < \mathrm{LCL}$	Comforting	Excellent

TABLE 3
. READING S CHART POINTS.

Point	Homogeneity
$\mathrm{UCL} \le \mathrm{S}$	Ruined
$\bar{\mathrm{S}} < \mathrm{S} < \mathrm{UCL}$	Very poor
$\mathrm{S} \cong \bar{\mathrm{S}}$	Poor
$\mathrm{LCL} < \mathrm{S} < \bar{\mathrm{S}}$	Good
$\mathrm{S} \cong \mathrm{LCL}$	Very good
$\mathrm{S} < \mathrm{LCL}$	Excellent

TABLE 4. READING X-BAR CHART PATTERNS

Pattern	Description	Homogeneity	IML
Cyclic	Points fall on alternate waves	Poor	Poor
Mixed	Points fall near to control limits	Good	Very poor
Stratified	Points cluster around a level	Good	Ruined→Good
Shifted	Points explore another center	Common	Common
Trended	Points have a monotonic direction	Very poor	Very poor
Perturbed	Points sharply fluctuate	Ruined	Ruined

The homogeneity of a pattern should be corrected by the homogeneity of its points from S chart. Also, IML of a pattern can be corrected by IMLs of its points from X-bar chart. A corresponding pattern on S chart can be used as a complementary interpretation for a pattern on X-bar chart. For instance, a cyclic pattern on S chart confirms that the inspection and maintenance process design isn't sufficient; and that is worst for a perturbed pattern. The patterns on X/MR charts can be interpreted in the same way. A weighting mechanism can be used to quantify these readings and to extract models for the corrosion process aided with the results of §4.1. For instance, the homogeneity of points can be estimated by their CVs.

Several control charts are constructed for MCV based on the case study variables. For simplicity, control charts in Figs. 4-7 are selected. These charts are based on combining internal and external corrosions since both are risky and they may lead to corrosion crack. Fig. 4, control charts for individuals (X/MR charts) are used to generally monitor corrosion defects; where MR is the moving range of individuals. Charts in Figs. 5-7 are used to monitor corrosion defects separating the three specimens for years 2006 and 2011. Latter charts are based on successive five points sampling from MCVs data. They demonstrate the effect of time and location change on the corrosion process

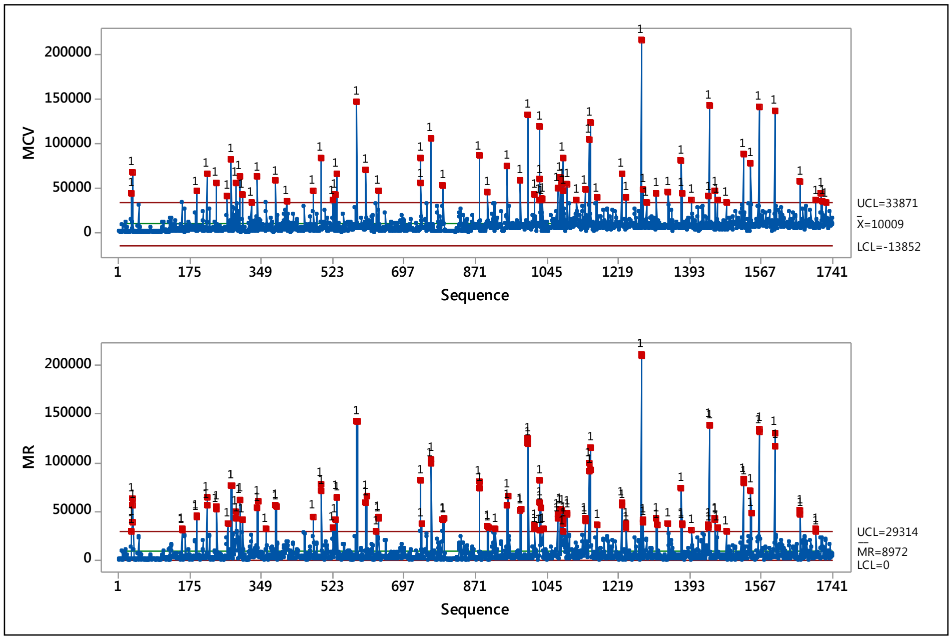
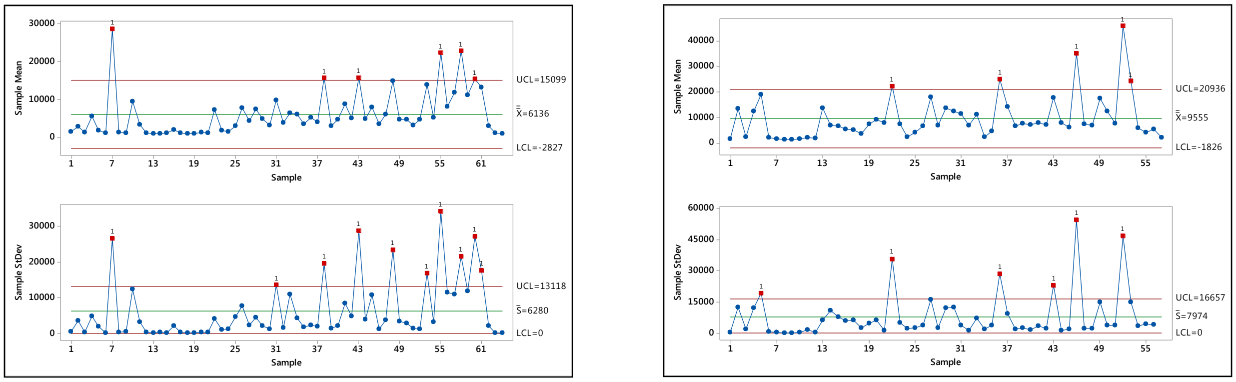


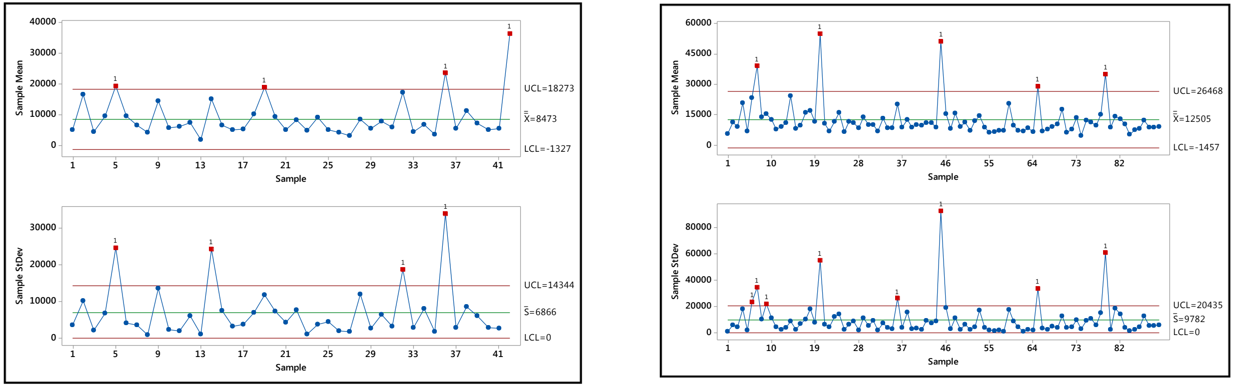
Fig. 4 X and MR charts for MCV

Fig. 4 gives an overview about the corrosion process, and it details and confirms the findings of Fig. 1. As seen a large number of points on both charts fall above UCL. Thus, the integrity of pipes is very low and the integrity management should be reinstalled.



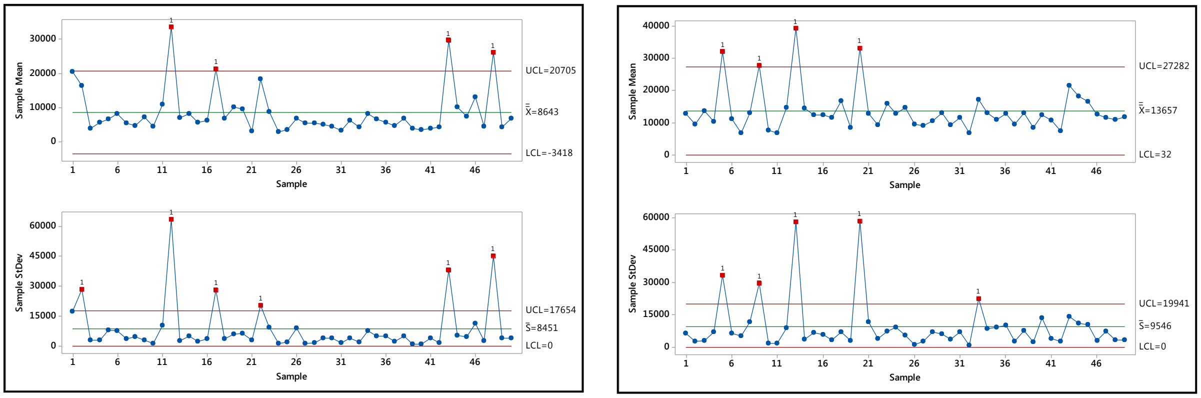
(a) Year 2006 (b) Year 2011

Fig. 5 X-bar and S charts for MCV of specimen 1.



(a) Year 2006 (b) Year 2011

Fig. 6. X-bar and S charts for MCV of specimen 2



(a) Year 2006 (b) Year 2011

Fig. 7 X-bar and S charts for MCV of specimen 3

Figs. 5-7 demonstrate a variety of patterns with out-of-control points and patterns, and confirm that the corrosion process as a whole is nonhomogenous and the state of pipes is instable. For instance, Fig. 5-a shows high perturbation in a big portion of the pipe specimen (points 37 to end) while slight enhancement appears on Fig. 5-b. This means that maintenance process made in year 2006 is better than that made in year 2001. Notice that all charts are very clearly readable and decisive and they don't need to exhaustive discussion. Thus, remaining charts can be qualitatively explained in the same way referring to Tables 2,4. The practioners can roughly interpret these chart information to have a conclusion about corrosion defects in the pipelines

V. CONCLUSION AND FUTURE WORK

A statistical methodology has been proposed as a guide to monitor the corrosion defects in pipeline and to assess their risk. Some heuristic formulae are developed for future extensive work. This new methodology is able to explicitly to predict the condition changes of pipelines over distance and time, and it can be flexibly extended to manipulate other variables due to the simplicity of control charts and other statistical rules used in the analysis. It comprises both quantitative and qualitative routines. It is mainly introduced to be a toolbox in pipeline integrity management. The methodology concludes that the integrity management of the case study isn't satisfactory for that old pipelines and should be reinstalled. Mainly, the schedule of inspection and maintenance processes may have preferred to be shortened or other inspection and maintenance system should be used.

The methodology promises a new and effective direction for pipeline corrosion analysis. In addition, other quality tools and decision support systems can be integrated into the proposed methodology in future work. In addition, some formulae will be proposed with a suitable weighting mechanism for the attributes in Tables 2-4. This to estimate several overall quantities such as homogeneity of corrosion process, severity of risk, risk indicator, and IML. These values will deliver better decision ground for the pipeline integrity. Furthermore, it can be extended to reliability modeling and prediction for pipeline systems.

There is an important question here; does soil type has effect on the internal corrosion? Or this change comes due to environment and location of specimens? If this is correct, then a soil may have some radiation or magnetic properties that improve or worsen pipe protection. To obtain a right answer, extensive material laboratory and statistical experiments should be carried out to differentiate the types of soil. The current unique interpretation for the high degradation of internal surfaces is the low level of integrity management specially the inspection plan. However, soil selection and treatments are still vital for pipe protection

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