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Optimization of Hydrogen (H2) Steam Reforming Units' Preventive Maintenance by Adopting Corrosion Prediction Tools

Defteraios N[1], Ziomas I[1*], Caroni C[2], Nivolianitou Z[3], and Aneziris O[3]

[1]Department of Process and Systems Analysis, Chemical Engineering School, NTUA, Athens, Greece

[2]Department of Mathematics, Physical Sciences School, NTUA, Athens, Greece

[3]Department of Radiological Sciences, National Center for Scientific Research, Demokritos, Aghia Paraskevi 15310, Greece

***Corresponding Author:** Nicholas Defteraios, Department of Process and Systems Analysis, Chemical Engineering School, NTUA, Heroon Polytechneiou 9, Zografos 157 80,Athens, Greece, E-mail: deftereosn@tee.gr, deftereosn@central.ntua.gr

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1. Abstract

The aim of this paper is to present a Risk-Based Inspection and Maintenance (RBIM) methodology adopting prediction models that depict the yearly corrosion rate per loop of an examined refinery unit, under different operating conditions (e.g. temperature, pressure, fluid speed), metallurgy and other related physicochemical variables. This prediction is very useful in the everyday operation of refineries and other industries involving similar corrosion risk. Corrosion measurements were obtained from a part of a large Greek refinery operating a 12-year-old H_2 steamreforming unit for its diesel desulphurization process. Wall thinning measurements by ultrasonic scanning equipment were grouped by period, unit section, steel alloy type, fluid type, and nature and processed by multivariable regression analyses. The outcome of these analyses is an extensive family of multivariable functions describing, with a defined accuracy, the yearly corrosion rate for each corrosion loop and each examined part of it. This provided the basis for the design and development of a tailor-made software with user-friendly data entry and reporting system to be used as an additional loss prevention tool by the refinery management team. Results regarding the tool implementation are presented in this paper.

2. Keywords: Multivariable regression; Corrosion prediction; Steam reforming; RBI

3. Glossary: CA: Corrosion Allowance; CML: Condition Monitoring Locations; CO_2: Carbon Dioxide; CR: Corrosion rate; DCS: Distributed Control System; H_2: Hydrogen; HTHA: High-Temperature Hydrogen Attack; IOW: Integrity Operating Window; PHA: Process hazards analysis RBI: Risk Based Inspection; TMI: Thickness Measurement Inspection; TML: Thickness Monitoring Locations

4. Introduction

Both the reliability and the safety of industrial equipment in the process industries are substantially influenced by degradation processes such as corrosion, erosion, deposits and blocking of pipes. Corrosion can trigger serious failures, which eventually lead to large economic loss, sometimes combined with environmental pollution, or risk of personnel losses, unpredictable and costly shutdowns of industrial facilities due to repair and replacement[8].

Erosion-corrosion is caused by a complicated interplay of a number of parameters. A large body of experimental work has identified several key variables that influence the rate of attack where their mix is mostly present during this phenomenon. Owing to this complexity, various inspection and corrosion prediction tools have been applied by the petrochemical industry and based on experience, in combination with a qualitative risk assessment of the mix of corrosion mechanisms' contribution to systems' deterioration. All these efforts have a common task to uniform as much as possible the inspection and maintenance scheduling and optimize cost without compromising in safety performance. One of the latest achievements in this sector is the Risk-Based Inspection and Maintenance (RBIM).

RBIM is a loss prevention 'tool' that started to be applied in the early '00s, accommodating the process industry needs to

*We regret to inform readers that Professor I. Ziomas passed away on Saturday 24th February, 2018.

improve their knowledge of equipment (machinery, piping etc.) health status, minimizing inspection and maintenance costs, while being on the safe side of operational procedures. Several RBIM tools have been developed so far [2-6].

The most common ones in the refinery/ petrochemical industry are the (RP) 580, Risk Based Inspection (RBI) framework, issued in 2002, which is accompanied by the (RP) 581, Risk Based Inspection Technology in 2008, providing guidance on developing a Risk-Based Inspection (RBI) program for fixed equipment and piping [17, 36]. In addition, there is currently a European effort to develop a similar but more inte-grated tool covering a wider range of different industry categories.

RBIM implementation presupposes the systematically prescheduled performance of 'ad-hoc' inspections of static equipment and other machinery, which, nowadays, are performed faster and provide more and more reliable results without any need for shutting down units, contributing thus to significant business continuity. This is in contrast to proactive maintenance that requires down-time minimization, especially in bottlenecked units [12,36].

State-of-the-art nondestructive techniques for process equipment metallic parts corrosion thinning and identification of spot irregularities are able to prevent uncontrolled incidents, e.g. ultrasonic echo attenuation method, amplitude based backscatter, velocity ratio, creeping waves, etc. The latter provide good outcome and are used alone or in combination with other methods to provide more reliable results in process piping, equipment shells or storage tanks and prior to deciding on any shut down for maintenance reasons.

The most familiar and widely used categories of corrosion types are summarized in the following eight forms:i) uniform attack, ii) crevice corrosion, iii) pitting, iv) intergranular corrosion, v) selective leaching, vi) erosion-corrosion, vii) stress corrosion, and viii) hydrogen damage, particularly known as Hydrogen under High-Temperature Attack (HTHA). Substantial advances in the field of corrosion science have led to clearer definition of the mechanisms of many forms of corrosion; however, rather than placing the mechanisms into distinct categories, the overlap between many of the forms has become greater [3,37].

The benefit of the study described in this paper is essential for the refinery and petrochemical community, where it can be used as a basis to determine the respective corrosion rate functions of corrosion loops or integrated units, based on statistical analysis of real wall thickness measurements. In this study, these functions have been implemented in a purpose made software for the extraction of the desired reports predicting the lifespan of the examined unit sections.

This effort is essential for the determination of risk analysis factors used in the RBIM methodology and provides proactive evidence for the determination of the breakeven point between the cost of the frequency of inspection and cost of maintenance and downtime resulting to significant business interruption as aftermath. This approach is quite common nowadays, as least cost strategies for asset management (operation, maintenance, and capital expenditures) are essential for increasing the revenues of refineries and petrochemical plants. This risk centred approach used in this study helps in making decisions regarding the prioritization of the equipment for maintenance and in determining an appropriate maintenance interval [21].

5. Methodology

5.1. Corrosion Rate

The corrosion rate for wall thinning damage mechanisms is determined by the difference between two thickness readings divided by the time interval between the readings. The determination of the corrosion rate may include thickness data collected in more than two different time periods. These periods may include one, two or even more years, depending on the particular item of equipment, the process involved and the risk assessed in terms of wall thickness reduction expected; the last is caused by the presence of a mix of corrosion and erosion mechanisms in com-bination with the metallurgy present defining a corrosion loop.

Suitable use of short-term versus longterm corrosion rates is defined. Particularly, shortterm corrosion rates are typically determined by two (2) yearly thickness readings, whereas longterm rates use the most recent reading and one taken earlier in the life of the equipment, usually those that describe an earlier stage after the construction of the unit under study. These different rates help distinguish recent corrosion mechanisms from those acting over a long period of time [8].

It is worth saying that what makes more sense in many units is the total impact of the corrosion mix both in the short and in the medium run. This is because of the difficulty in identifying an adequate number of wall thickness measurements over extensive time series making possible the distinguishing and predicting of corrosion rates per loop. This becomes more complicated in expansive units involving hundreds of piping meters of various sizing and numerous equipment parts.

The total corrosion rate of piping and equipment exposed metallic parts owes to a mix of mecha-nisms that may differentiate per different corrosion loop. A quite significant part of this rate can be determined quantitatively by the difference between two readings of wall thickness divided by the respective time interval. By this approach, calculations can include data of wall thicknesses which is collected in different time periods. These periods may refer to one, two or even more years, depending on the equipment part, the process involved and the risk that it is assessed, in correlation with the anticipated wall thickness reduction per loop.

5.2. Condition Monitoring Locations

Condition Monitoring Locations (CML) are designated areas on piping and pipe fittings where periodic examinations have been proactively decided upon to monitor the rate of corrosion, which is measured as the yearly wall thickness reduction rate. These locations are categorized and prioritized per corrosion loop sharing similar physicochemical conditions (e.g. temperature, pressure, the presence of liquid, gas or mixture of them), type of fluid and soluble or insoluble impurities involved; the actual metallurgy involving different carbon steel alloys and stainless steel in various process loops is also considered [8,30].

Selected loops incorporate monitoring locations on pipe and associated fittings' wall thickness, which have been qualitatively assessed to be associated with corrosion mechanisms dealing with physicochemical, electrochemical and high temperature hydrogen attack reactions and possibly with stress cracking, where such information is available. Wall thickness is monitored by prescheduled measurements in a time frame that fulfils production demand restrictions. This time frame is on average one year, not always including the same monitoring locations though.

The yearly corrosion rates, the lifespan and the next inspection intervals are all calculated to determine the limiting component [7]. As a result, corrosion loops with high failure potential caused by increased risk will require more frequent monitoring. The designated areas on piping and fittings, where periodic examinations were conducted to monitor the presence, and the rate of wall thickness reduction were the: a) Elbows, b) T-connections, c) Reducers, d) connections with instruments commonly found in examined units (e.g. pressure indicators, flow meters, etc.), and e) points of linear pipe parts.

The yearly Corrosion Rate (CR) of the CML is determined within a period of two (2) measurements and has been calculated with the following formula:

$$\text{Corrosion Rate - CR (mm/year)} = [(mm_{latest} - mm_{previous}) / (t_{latest} - t_{previous})]/[\text{ years } (t_{latest} - t_{previous})] \quad (1)$$

where,

mm_{latest} = the wall thickness at a CML in mm measured during the most recent inspection.

$mm_{previous}$ = the thickness at the same CML in mm, either on the first thickness measurement at this point, or at the start of a new corrosion rate environment, or as measured during a previous inspec-tion.

If there are more than two (2) periods of measurements for the same CML, then the Yearly Corrosion Rate (CR) is calculated by the following equation and it equals to the weighted average of the sub-corrosion rates per examined period.

$$Corrosion\ Rate\left(\frac{mm}{year}\right) = \frac{\sum_{j\geq3}^{n} CRj\ X\ tj}{\sum_{j\geq3}^{n} tj} \quad (2)$$

where,

CR_j = the subcorrosion rate per period,

t_j = the examined periods in years.

The Lifespan of the examined pipe or equipment part was evaluated by the following formula:

$$\text{Lifespan (years)} = [(mm_{present} - mm_{allowed})] / [\text{CR (mm/year)}] \quad (3)$$

where,

$mm_{present}$ = the wall thickness in mm of a CML referring to the present value of the latest measure-ment (mm_{latest}), converted by applying a prediction tool.

$mm_{allowed}$ = the minimum wall thickness in mm at the same CML down to the Corrosion Allowance (CA).

The Predicted Wall Thickness after a specific time span (number of years) that is less than the lifespan (in years), is given by the following formula:

$$\text{Predicted Wall Thickness } (mm_{predicted}) = [mm_{present} - \text{CR (mm/year)}] / \text{years } (t_{predicted} - t_{present}) \quad (4)$$

where,

$mm_{predicted}$ = the wall thickness in mm of a CML predicted for a future time point.

$mm_{present}$ = the wall thickness in mm of a CML referring to the present value of the latest measurement (mm_{latest}) converted by applying the prediction tool.

6. The Case Study

The case study, from which corrosion measurements have been taken, refers to a 12–year-old 'Hydrogen Production Steam Reforming Unit' located in a refinery of the Hellenic State. The unit is able to produce nominally 65,000 Nm3 of H2 per hour. The design of the unit was based on various feeds such as natural gas and, stabilized naphtha (less used) or even mixes of naphtha and LPG. The key stages of the process are: a) the desulphurization, b) the prereform, c) the steam reforming, d) the conversion of carbon monoxide through a shift reaction, e) the purification of the hydrogen stream in the absorbers, f) the steam production using the energy of combustion, and g) the burning in the ovens.

Natural Gas represents 95% of the total current unit feedstock also containing carbon dioxide, helium, hydrogen sulfide and several other compounds (impurities) in a smaller percentage. In particular, [33] suggests that carbon dioxide (CO2) and hydrogen sulfide (H_{2S}) are 'acid' gases that can cause extensive corrosion damage on carbon and other alloy steels in the presence of water in unit sections before the step of desulphurization. The concentration of such impurities may vary significantly depending on the Natural Gas feedstock provider. The same can apply to Naphtha as a feedstock, where sulfur hydrocarbons may also exist in a variety of forms. Moreover, the aggressive behavior of hydrogen under high temperatures (HTHA) is expected to be present in a lot of stages of the process and especially in the stage of steam reformation [3,6, 34].

6.1. Data Analysis

Most of the data analyzed has been obtained during the prescheduled periodic shutdowns when preventive and corrective maintenance is usually performed. Data collection has been performed using specific ultrasonic testing equipment, specialized for steel piping wall thickness measurements; the standard error provided by the instrument manufacturer has been also considered. Calibration of the equipment was always ensured before its use in the field for data collection. The former takes place on 'standard' pipe pieces and fittings, which are considered to be of the same type and specifications as the ones that have been used in the surveyed corrosion loop.

During measurement, the thinnest reading or an average of several measurement readings taken from the area of a specific CML are recorded and used to calculate the corrosion rates; this CML corresponds to a particular angle of the pipe or of a fitting.

The most common method that is used to address corrosion is to specify the Corrosion Allowance (CA), which is given by the manufacturer of the steam-reforming unit. This value is a supplementary metal thickness that is added to the minimum thickness and is considered as a "sine qua non" condition for the pipe/fitting to resist the applied loads. CMLs at the examined unit are points located upon piping, process equipment shell or internal parts (e.g. coils) and process equipment external surface that have been preselected by their manufacturer. In this process, API guidelines are followed in combination with the anticipated mix of corrosion mechanisms expected to be present, such as a combination of galvanic corrosion with HTHA uniform and pit corrosion.

Records of all examinations in CMLs are initially handwritten on isometric drawings by the unit maintenance personnel performing such wall thickness measurements; the former are then transformed to a softcopy format, so as to allow easy identification of their exact position, ensuring future repetition of measurements, as needed, and the accurate calculation of the Corrosion Rate (CR). Wall thickness readings are further transferred to EXCEL (Xls) spreadsheets for further categorization, sorting, analysis and extraction of preliminary data source tables, which are finally used in the statistical analysis.

The following tables provide indicative information on wall thickness measurements for a part of a corrosion loop.

6.2. Statistical Analysis

The step following the grouping of wall thickness measurement results by period, unit section, steel alloy type, fluid type and nature, size of pipe, and presence of fittings (e.g. T-connections, el-bows, size reducers, taps) is the statistical analysis of this data; this is done through the application of a series of multivariable regression analyses performed in the 'STATA 14' statistical software [8] to assess the accuracy and the presence of possible non-linearity in the model. These analyses have been performed both separately for each sectional corrosion loop, where a similar mix of metallurgy is present, and globally including all process sections as one integrated unit. It should be noted that the particular design approach of the specific unit follows the generic rule of a standard metallurgy per section, thus simplifying regression analysis and modelling.

For this analysis mathematical models were assumed to elaborate these linear regressions, where the unknown coefficients in the regression equation have been calculated from the wall thickness measurements on CMLs. The generic form of the simplest multivariable linear regression fitted (prediction) model adopted for the regression analysis is presented in the following generic equation:

$$\frac{\hat{Y}_i}{year} = \hat{b}_0 + \hat{b}_1 X_{i1} + \hat{b}_2 X_{i2} + \hat{b}_3 X_{i3} \dots \hat{b}_k X_{ik} \quad (5)$$

where SST=SSE+SSR. The coefficient of determination or R_2 is a number between 0 and 1 as long as the regression contains an intercept and is given by the equation R^2=SSE/SST or R^2=1+SSR/SST. It actually measures the goodness of the regression, i.e. what part of the sample variation of the Y's is explained by the sample variation in the X's. The closer the approach to 1, the better the fit of the model to the experimental results [26,27].

Given that the examined unit is nearly 13-years old and has been designed with state-of-the-art technology requirements, the volume of wall thickness measurement data was quite limited; there were few repetitions within two or three different time intervals at the same condition monitoring locations of sectional corrosion loops. Unrepeated measurements have been omitted from the statistical analysis although they provide essential information about the variance of the nominal wall thickness and the actual one, as they confirm the accuracy of the models extracted.

The regression method applied was based on the available data and the need for combining 'ideally' all involved variables together describing the corrosion conditions per loop. This contained the testing of a wide range of linear, exponential, logarithmic, power and a combination of all above models on all independent values, ensuring the best fit of the derived model to the experimental measurements. Dummy variables were considered for distinguishing different corrosion loops involving variations in metallurgy and/or nature of fluid involved in the pipe network. The results of this methodology include a family of multivariable functions Yi describing the anticipated yearly corrosion rate (CR) in each corrosion loop, incorporating all corrosion mechanisms that were present in each case; their effect is depicted by the wall thickness values that can be used in both short (~1 year) and medium (~2-5 year) term predictions. On the long-run, this approach does not provide a reliable fit to the measurements, unless adequate repetition of regressions is periodically performed.

7. Results

7.1. The Models

In the previous section, we have described the process that resulted in linear regression models providing acceptable accuracy in a series of corrosion loops representing nearly 50-60% of the unit piping involved. However, areas involving single (unrepeated) measurements have been currently omitted from the regression, because the analysts considered that nominal wall thicknesses cannot be taken into account as initial measurements. This limitation was dictated by the observation that significant tolerance has been reported by pipe & fittings' manufacturers themselves reaching +/-15% of their nominal dimensions. The same tolerance ratio applies to equipment parts as well. It has been foreseen in the present models that potential expansion of measurements through the institution of additional CMLs can be incorporated in the modelling process, thus comprising additional corrosion loops.

The two (2) models proposed are multivariable functions providing information about the annual corrosion rate Yi, per loop and per CML. These functions are correlated with Xik variables, namely Temperature (T), Pressure (P), fluid Velocity (V), linear pipe and pipe fitting Diameter (D), as well as with dummy variables taking 0 and 1 values, such as type of fluid (Ft), and the presence of fittings (FT). Metallurgy (M) involved in different corrosion loops is a dependent variable to the type of fluid (F) at the sections examined (only to specific alloys can be used for specific fluids); therefore, the former is omitted.

Considering the above, the first linear approach is the following equation for all loops:

$$\frac{Yi}{year} = \hat{b}_0 + \hat{b}_1 PH_i + \hat{b}_j F_{ij} + \hat{b}_z M_{iz} + \hat{b}q PSi\ FTiq + \hat{b}2Ti + \hat{b}3Pi + PSi(\hat{b}4Di + \hat{b}5Vi) \quad (13)$$

where,

PH= dummy variable representing the fluid nature.

F= dummy variable representing the fluid type.

M= dummy variable representing the metallurgies.

FT= dummy variable representing fitting types or the presence of linear pipes.

T= temperature (C°).

P=pressure (bar).

PS= dummy variable representing the presence of piping systems.

D= pipe nominal diameter (inch).

V= fluid speed (m/sec).

The above equation creates a series of linear nomographs depicting the predicted yearly corro-sion rate per temperature, pressure and pipe size variation (where applicable). Indicative linear nomographs are given in the following (**Figure 1**and **2**).

The second modified linear approach with logarithmic variables goes similarly, as in the following:

where variables specifications are the same as in the simpler linear function (13) ones.

$$\frac{Yi}{year} = \hat{b}_0 + \hat{b}_1 PH_i + \hat{b}_j F_{ij} + \hat{b}_z M_{iz} + \hat{b}_q PSi\, FT_{iq} + \hat{b}_2 \log(T_i)^{-2} + \hat{b}_3 \log(P_i)^2 + \hat{b}_4 PSi(D_i/V_i)^{0,1} \quad (14)$$

An application example of function (14) is presented here. In the corrosion loop j=HYH (Hydrogen/Hydrocarbons), the piping metallurgy is throughout carbon steel, z=C0036C, the CML is an elbow, 90° the pipe diameter is D=4inch (~100mm), the fluid velocity is V=5m/sec, the fluid temperature is T=50°C, and its pressure is P=14bar. Then the dummy variables of the model take the following values:

$PH_{HYH} = 0$ as fluid is in gas format.

$F_{HYH}=1$ and all the rest are 0.

$M_{C0036C} =1$ and all the rest are 0.

$FT_{90}{}^{o} = 1$ and all the rest are 0.

PS=1, referring to pipe systems.

The regression model fitted coefficients produced are:

$\hat{b} = -0,75712$

$\hat{b}_{HYH} = 0,19288$

$\hat{b}_{C0036C} = 0$ (because of the collinearity presence with the HYH)

$\hat{b}_q = -0,03366$

$\hat{b}_2 = 0,34215$

$\hat{b}_3 = 0,31932$

$\hat{b}_4 = -0,00756$

and the prediction for the corrosion rate at this point is CR=0,031mm/year.

7.2. The Developed Software

The whole procedure of data collection, analysis and models implementation culminated through the tailormade the development of a software tool. This tool is a user-friendly designed database for in-house by the oil refinery maintenance personnel that comprises three (3) main parts; a) the Data Entry, b) the Data Processing, and c) the Results Extraction. In more detail:

7.2.1. Data Entry: This is divided into two (2) main sections. The first (1st) concerns the import of all detailed key elements that describe the examined equipment and the prevailing operation conditions. This is specific data related to the various process steps, to the equipment and piping features, as well as to the physicochemical properties of the substances involved. Example entries of this data include (but are not limited to) coded information of metallurgy, dimensions and type of equipment parts, nature of fluid involved, type, volume and fluid speed, prevailing corrosion mechanisms and nominal fluid physical conditions, such as temperature and pressure. In addition, PDFs of technical details and drawings of equipment together with indicative information related to interesting inspection findings and maintenance actions are also included. The software tool has been developed in Microsoft Access©, while the GUI headings are in Greek; two screenshots of the tool are presented in (**Figures 3** and **4**) depicting Data entry for Definition of conditions per loop on the left and Measurements per CML on the right.

In general, Data entry is relatively simple insofar as specialized personnel defines the corrosion loops and the associated anticipated mix of corrosion mechanisms, adds the examined lines and the equipment, and all respective CMLs, and then ensures that wall thickness measurements data is updated.

7.2.2. Processing: This part includes all essential forecast and risk assessment functions, aiming at the determination of lifespan or the anticipated corrosion per predefined period of the examined equipment parts referring to particular CMLs; it also deals with the respective prioritization of risk. Namely, the family of the above described multivariable functions with logarithmic variables are applied (function 14) by adopting the implementation functions 1,2,3 and 4 for the predictions.

The simplified forecasting approach proposed by the multivariable function is depicted in the graph of (**Figure 5**).

The diagram in Figure 5 results from the typical scenario and shows the curve which is defined by two (2) minimum past measurements values performed at different years t_1 and t_2 at the same CML, where a standard error has been co-estimated. If more than two (2) measurements are available, then function 2 is applied for "n" measurements at t_j periods. When applying the function at the specific CML, the first step is to determine both the present value of the wall thickness and the value at a later stage (at the end of the desired prediction period) and up to value of the corrosion allowance. This is achieved by extending the curve until the desired time (t) and then by reading the respective value on the Wall Thickness (mm) axis of the graph; the software performs this calculation automatically. Similar approaches may be applied in newly established CMLs located in already examined corrosion loops, where there is either only one (1) measurement available or alternatively by taking the nominal thickness value deducting the tolerance provided by manufacturers; however, in this case prediction results involve a much higher error, which should be co-estimated by the unit operation engineers.

The above prediction is additionally tested (per CML), by applying a simple linear function which is based solely on the experimental data per CML, provided that there are minimum two (2) measurement values availalbe for two different periods. The logic of the function is based on the following standard model:

$$Y(Xi)/year = \alpha X + \omega \quad (15)$$

where,

α = the slope of the straight line that defines the corrosion rate,

X = the time (in years)

ω = is equal to the original actual thickness of the wall.

This approach is simple and is based solely on the experimental data. The function of equation (15) creates a straight-line with negative slope ($\alpha<0$), which is defined by the first and the last measurement performed at different times t_1 and t_j; by extending the line down to the corrosion allowance or to any desired future time instant, the interested analyst should normally not have big deviations from the prediction model developed in this study; in a different case, function (14) should be re-examined. This is only a qualitative testing tool with the purpose to warn operators that the prediction model needs fine-tunning or/and data need additional checking.

7.2.3. Risk Analysis: This step incorporates an additional semi-quantitative risk analysis per corrosion loop, assessing the likelihood and the consequence of the failure mechanisms. The likelihood is evaluated upon the determination of various factors, such as a) the age of the equipment, b) the history damage to components, c) the corrosion rate, and d) the estimated number and combination of corrosion mechanisms. The consequences of an instantaneous or continuous energy release (e.g. explosion or fire) is similarly assessed by defining the type of liquid and its flammability or combustibility, its quantity, the presence of bottlenecks in the process and the possibility of anticipating a shut down of the unit and a total cessation of operations. The risk assessment incorporates the assessment of the present and the expected serviceability of equipment by answering to the following questions: what material and equipment involved is expected to be worn or damaged;) what is the likelihood of such material to suffer the damage; and what are the consequences of the loss scenario described.

This methodology is qualitative, incorporating, though, some quantitative parameters, (e.g. the quantity of the fluid and its pressure & temperature), with the aim to distributing associated risk per corrosion loop, and per equipment part. The analysis poses questions and leads to more accurate results with respect to the quite general commonly applied qualitative analyses and, therefore, it avoids an excessively conservative classification of risk. This level of assessment adopts an 8 x 8 matrix to display the risk level results.

7.2.4. Results Extraction: The third part of the tool is the one that deals with reports extraction, either onscreen or as EXCEL or PDF documents as well. These reports involve expansive lists of coded CMLs, sorted per equipment part and corrosion loops; filters are also provided for selective access to data. Example screenshots of these reports are provided in (**Figures 6** and **7**), referring to Measurements list per corrosion loop on the left and to corrosion prediction and confirmation values on the right.

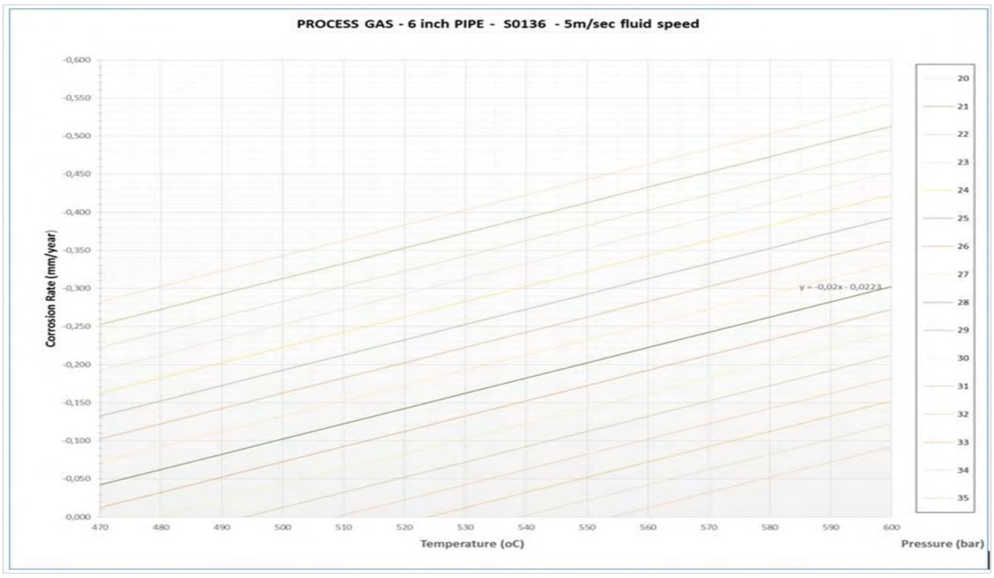

Figure 1: Corrosion rate – ‘Process Gas’ loop

Figure 2: Corrosion rate – 'Hydrogen & Hydrocarbons' loop

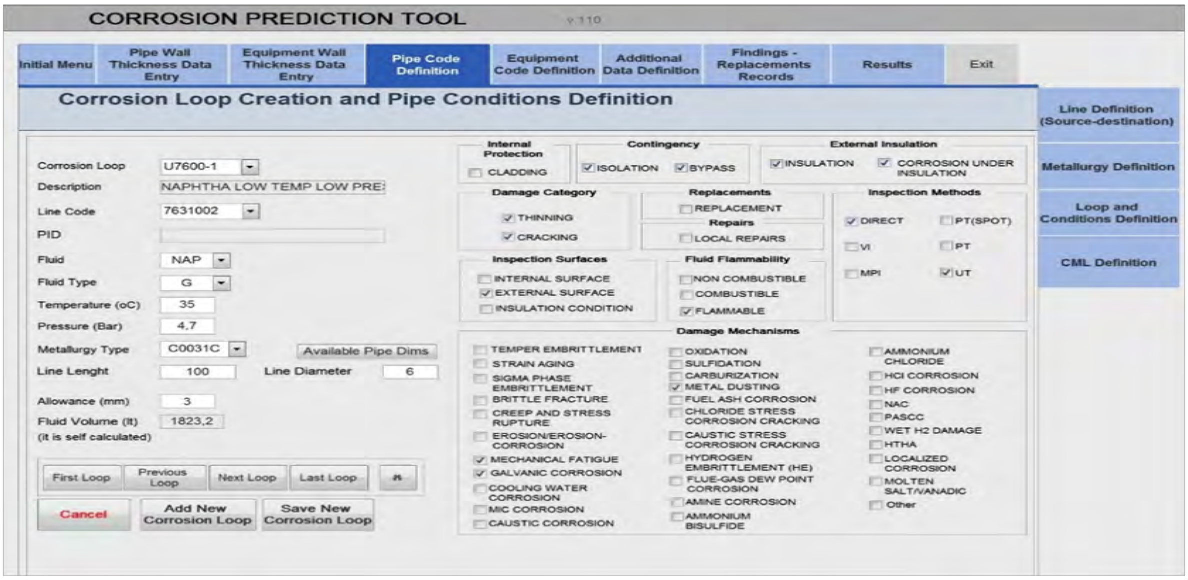

Figure 3: Data entry – Definition of conditions per loop

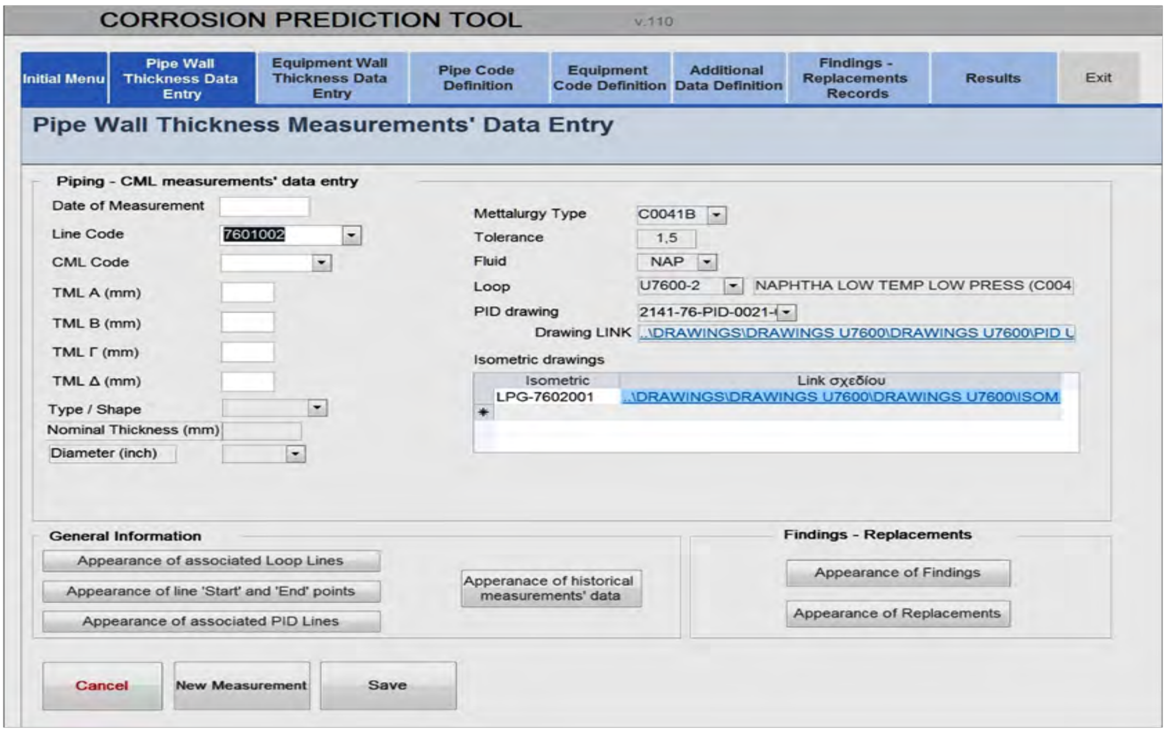

Figure 4: Data entry - Measurements per CML

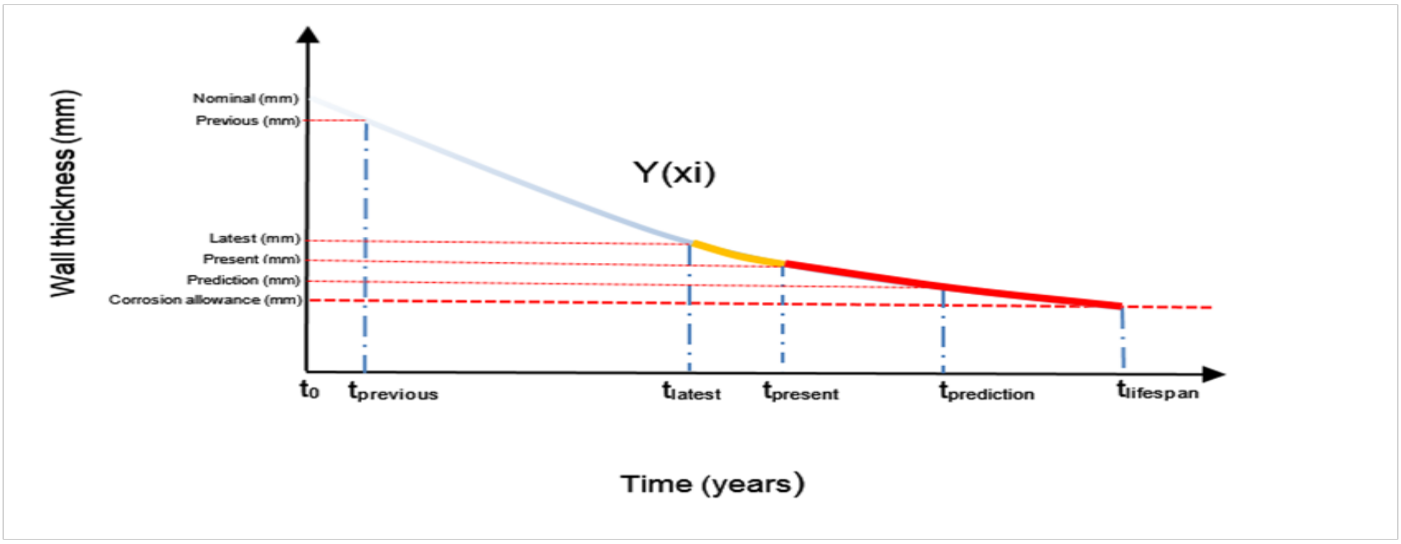

Figure 5: Typical multivariable function graph per CML

Pipe Measurements Historical Data — Πέμπτη, 1 Νοεμβρίου 2018 9:43:12 μμ

Loop	Line	CML	Type	Nom.Thic.	Fluid	Nature	Press.	Temp.	Metalur.	Specs	Diam.	Date	A	B	Γ	Δ
U7600-6	7602001	1	L	7,632	LPG	G	15	40	C0033C		3					
U7600-6	7602001	2	L	7,632	LPG	G	15	40	C0033C		3	18/4/2016	7,8	7,7	7,6	
U7600-6	7602001	3	R	7,632	LPG	G	15	40	C0033C		2	18/4/2016	7,5	7,6		
U7600-6	7602001	3	R	7,632	LPG	G	15	40	C0033C		3	18/4/2016	7,8	6,8		
U7600-6	7602001	4	R	7,632	LPG	G	15	40	C0033C		2	18/4/2016	7,2	7,5		
U7600-6	7602001	4	R	7,632	LPG	G	15	40	C0033C		3	18/4/2016	7,6	7,5		
U7600-6	7602001	5	L	7,632	LPG	G	15	40	C0033C		3	18/4/2016	7,8	7,2	7,7	
U7600-6	7602001	6	T	7,632	LPG	G	15	40	C0033C		3	18/4/2016	10	11,9	10,3	
U7600-6	7602001	7	L	7,632	LPG	G	15	40	C0033C		3	18/4/2016	8	7,7		
U7600-6	7602001	8	R	7,632	LPG	G	15	40	C0033C		2	18/4/2016	7,8	7,5		
U7600-6	7602001	8	R	7,632	LPG	G	15	40	C0033C		3	18/4/2016	9,6	10,4		
U7600-6	7602001	9	45	5,54	LPG	G	15	40	C0033C		2	18/4/2016	4,3	4,6	4,6	
U7600-6	7602001	10	L	5,54	LPG	G	15	40	C0033C		2	18/4/2016	5,9	5,5	6	
U7600-6	7602001	11	L	5,54	LPG	G	15	40	C0033C		2	18/4/2016	6	6,1	6,4	
U7600-6	7602001	12	90	5,54	LPG	G	15	40	C0033C		2	18/4/2016	5,1	4,8	5,1	
U7600-6	7602001	13	L	5,54	LPG	G	15	40	C0033C		2	18/4/2016	6	6		
U7600-6	7602001	14	L	5,54	LPG	G	15	40	C0033C		2	18/4/2016	6,6	7		
U7600-6	7602001	15	L	5,54	LPG	G	15	40	C0033C		2	18/4/2016	4,3	4,5		
U7600-6	7602001	15.1	L	5,54	LPG	G	15	40	C0033C		2	18/4/2016	3,9			
U7600-6	7602001	16	T	5,56	LPG	G	15	40	C0033C		0,75	18/4/2016	5,5			
U7600-6	7602001	17	T	5,56	LPG	G	15	40	C0033C		0,75	18/4/2016	5,6			
U7600-6	7602001	18	T	5,56	LPG	G	15	40	C0033C		0,75	18/4/2016	5,5			
U7600-6	7602001	19	T	5,56	LPG	G	15	40	C0033C		0,75	18/4/2016	5,4			

Figure 6: Reporting – Measurements list per corr. Loop

Pipe Corrosion Prediction Report CMLs with Measurements — Παρασκευή, 9 Νοεμβρίου 2018 2:20:03 μμ

Loop	Line	CML	Nom. Thick.	Tolerance	Prediciton Years	Log. Thickness Prediction	Log. Life Expect. Prediction	Thichness Comfirmation	Life Expect. Prediction	Risk
U7600-4	7654004	1	6,35	3	3			7,11	94,9	3
U7600-4	7654004	2	4,55	3	3			3,925	29,4	3
U7600-4	7654004	2-3.1	6,35	3	3			8,08	49,9	3
U7600-4	7654004	2-3.2	6,35	3	3			7,805	56,3	3

Figure 7: Reporting – Prediction and confirmation

8. Discussion of Results

Hydrogen steam reforming units operate on a mixture of feedstock composed of natural gas, naphtha, or LPG streams or a mix of them, produced in other subunits of large oil refineries, under particularly demanding conditions owing to severe corrosion of their piping and pieces of equipment. The metallurgy mix and wall thickness used for these components is prescribed exactly by the relevant international codes. In the present study, the corrosion loops have been selected upon specific operating design codes, having also average inlet stream quality synthesis.

Designers and operators do take into account the corrosion rates cited in the literature or given by uniform experimental data (e.g. Nelson graphs); they also consider the recommendations produced from the root causes analysis of past incidents. Based on this bank of knowledge, the manufacturers propose the anticipated range of operating conditions for each piece of equipment and piping, including key factors such as the operating pressure & temperature, the exact synthesis of the fluid present in the loops, together with its speed and the geometry of pipings and vessels; this information is applied in the metallurgy mix selected and in the nominal wall thickness and corrosion allowance values defined per loop. However, nowadays oil volatility prices pose a strong requirement to oil refineries operators for a "flexibility" in the selection of the inlet stream mix per periodic demand proportion and quality wise; this policy results in significant operational cost earnings, as it is well known that the cost of raw materials is directly reflected in the expected gross profit margins, relatively narrow in recent years. This choice may also have as a result of the selection of inlet streams away from plant designers' prescriptions; the former may also contain impurities and their mix may have a composition that creates a stressful environment for the plant metallurgy mix, thus creating bigger uncertainties in the expected lifespan of such hydrogen units. For the sake of illustration, one could pose the question, 'what if, we increase the ratio of naphtha to natural gas in the Hydrogen steam reforming unit feed stream"? Experimental data obtained by performing real tests within such units has shown that the consequence is increased temperature and pressure in the main vertical tube of the catalytic furnace and the respective process fluid and hydrogen streams; these conditions by default increase the hydrogen attack (HTHA) phenomenon. Similar results could be assumed for other corrosion mechanisms, making the prediction in the change in the corrosion rate highly uncertain in most of the cases.

The functions proposed in this paper and the nomographs obtained from them provide a practical tool to refinery operators for assessing the expected corrosion rate upon changing specific conditions (e.g. temperature and pressure), which directly affect the synthesis of inlet streams, for particular pipe/fitting sizes. In addition, they can be used as additional tools for predicting the aver-age corrosion rate in the short and medium period of time. It is also worth mentioning that methodology errors are a summation of standard error(s) given by the ultrasonic instruments per se and the technology involved in wall thickness measurements, augmented by the measurement error; the latter is affected by both the human element and the process restriction factors involved in the calibration of the instruments, the selection of the monitoring locations, the repetition of meas-urements at the same points, the execution of measurements in all three pipe transverse axes, the fluid nature, its condition and speed traversing the pipes, and the cleanliness (lack of corrosion) of the external surface of the pipe. Analyzing in particular the ultrasonic technique related errors, the following factors can affect the ability of the former to accurately make thickness measurements:

8.1. Calibration

Since material thickness is calculated using a "known" velocity value, any difference between the actual material velocity and the velocity used for instrument calibration will result in a skewing of the ultrasonic thickness measurements. Therefore, ideally, instrument calibration would be performed on a known thickness of a material identical to that being tested. In reality, that is usually not possible. Instead, either the "known" velocity for carbon steel or a carbon steel calibration block is used to perform the calibration.

8.2. Surface Condition

The surface condition is an important factor to consider when any type of instrumentation is used; though, it is particularly important to consider this factor, when using a digital thickness gauge. Thickness gages are meant to be used where both surfaces are smooth, flat and parallel. If the surface under the transducer is rough, excess couplant can be trapped between the transducer and surface, resulting in erroneous readings. Further, if the back wall is rough, the ultrasonic pulse can be distorted or scattered, resulting in erroneous readings. Additionally, any loose or flaking scale, rust, corrosion or dirt on the surface of the part must be removed as it will interfere with the coupling of the sound energy from the transducer into the material. Lastly, though it is possible to make measurements through thin (a few thousands of an inch) layers of tightly adhered paint, thick paint will attenuate the signal and may create false echoes.

8.3. Part Geometry

Curved surfaces of pipes make acquiring accurate measurements more difficult. The center of the transducer must be held steady and perpendicular to the pipe while the measurement is being made. As the transducer gets larger in diameter, the ability to hold the transducer steady and perpendicular to the pipe becomes more difficult.

Couplant: A couplant is a material (usually liquid) that facilitates the transmission of ultrasonic energy from the transducer into the test specimen. When making measurements in the pulseecho mode, it is essential that the couplant layer be as thin as possible, otherwise, the thickness of the couplant will be included in the read-out of the material thickness.

8.4. Transducer Characteristics

Single element transducers depend on the front and back surfaces of the test piece being parallel. When this condition is met, a wide range of thicknesses can be accurately measured. If the surfaces are not parallel and/or if the surfaces are rough or corroded, a dual element transducer should be used. A limitation of the dual element is that it has a limited thickness range over which it can operate linearly [35].

The total error created because of the above factors is usually significant, especially when measurements are performed by in-house technical personnel or when different instruments are used over the examined periods. Although the repetition of measurements in the present case study is quite limited, both regression analyses proved that the statistical measure of how close the data are to the fitted regression line, namely R^2 reaches 0,5. In addition, the modified function (14) with logarithmic variables shows much better and more acceptable P-values (<<0,05), than the lin-ear function (13). However, macroscopically both equations provide similar results, a fact that demonstrates the applicability of the linear nomographs in the medium run.

Further studying of the example in section 5.2 shows that the annual corrosion rate at the HYH loop of a particular four inches size fitting (namely, a 90^o elbow), is approximately 0,031mm/year, at fluid Temperature of 50^{o}C, fluid Pressure of 14bar, and fluid speed of 5m/sec. The scenario of temperature increase (↑) by 10^{o}C, with all other variables remaining constant, will result in a corrosion rate increase (↑) up to 0,047mm/year, almost fifty per cent (~50% ↑) higher than in the molder conditions. This temperature increase may be the result of a possible change in the inlet feedstock mix and its enriching with additional naphtha instead of natural gas.

The operational cost gain owing to this variation should be weighed against the reduction in a particular unit's loop life expectancy so that the total operational cost breakeven point can be assessed. It must be admitted, however, that the error of the methodology is relatively large at present stage, owing to lack of sufficient statistical evidence. In this logic, interventions to inlet mixes can be assessed proactively in more detail so that refineries will be able to control costs and production schemes according to market demand, while simultaneously not compromising safety.

9. Conclusions

A method for determining sectional corrosion rate prediction tools in a hydrogen steam-reforming unit is presented in this paper; a software tool has been additionally developed aiming at assisting plant operators and managers in the efficient running of their asset. This tool, composed of multiple functions, has been assessed by means of regression analyses of wall thickness measurements performed in pipes and pipe fittings over the past 12-years of unit operational life at preselected Condition Monitoring Locations (CMLs). Despite the fact that the number of measurements available is rather limited letting space for higher uncertainty of results at this stage, regression models have been all the same constructed and nomographs have been created in view of future upgrading when a sounder statistical body is constructed. These functions and the associated software can assist oil refinery operators in assessing the possible effect on the examined unit performance, should any small changes to the inlet fluid mix be applied following oil market speculation. Additionally, the developed tool sustains the implementation of the RBIM techniques in the standard operating procedures of oil refineries, aiming at the optimization of periodic maintenance intervals in specific corrosion loops and in risk-prone unit sections.

Significant efforts have been recorded in designing and developing RBIM related software focusing on the risk assessment of corrosion loops so far; these are rather general purpose approaches giving "rule of thumb" results for a class of similar industries, involving linear approaches that provide good results only in the shortrun. The proposed methodology goes one step further, as it examines detailed Condition Monitoring Locations (CMLs) per loop and provides non-linear based predictions fitted to the experimental results with a given predetermined expected error.

The main limitation of the study is the high anticipated error in medium and much more in longterm predictions, as well as the lack of provision of any prediction related to corrosion loops without or with limited repetitive experimental results. The resulting less-accurate predictions are heavily related to the limited number of experimental results, impacted also by shortcomings of the ultrasonic scanning methodology per se. These disadvantages may be mitigated by 'rerunning' regression analyses on frequent intervals incorporating new evidence of updated wall thickness measurements, whenever possible. However, the inhouse developed software has adopted an additional 'control' function that provides linear based predictions, based on two past measure-ments per CML and expanding it down to the Corrosion Allowance (CA); in this way, the regression model may be additionally tested by this simple linear model, where cross-check data is available.

The proposed CML regression-based nonlinear prediction model can readily prove its usefulness, when used as an additional Decision-Making Tool in defining more accurate inspection and maintenance intervals; this will lead to savings associated with Risk Informed decisions and in direct cost reduction, if the inspection/maintenance run times can be modified (relaxed or intensified) with a certain degree of confidence. Indirect cost reduction is also expected when deeper knowledge on the total (measurable) effect of the corrosion mechanisms to equipment help prevent undesirable downtime and business interruption (BI) as aftermath. This effect may be vital, especially for units, such as the examined steam reforming, that possess unique pieces of process equipment leading the whole refinery on hold in case of failure. This configuration may be present in other refineries or petrochemical complexes sub-units as well.

The notion of overall Risk-Informed Decision Making in inspection and maintenance in refineries is promoted through the creation of the respective Risk Matrix, where several significant aspects have been aggregated. These aspects include monitoring of cost, reliability, maintainability and system availability; all factors should be treated simultaneously at the modelling of the decision maker's preferences structure proposing suitable inspection intervals that take into account the consequences involved [16]. For this reason, Multi-Criteria Decision models should be pursued using the current study results as additional criteria for defining the trade-offs between earnings and plant downtime.

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