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# A Planning Model for Inspection and Replacement of Pipes in a Refinery Plant

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Corrosion is a major safety issue that can lead to unexpected failures in refinery plants. Ensuring the safety of refinery processes from corrosion requires regular maintenance procedures such as the inspection and replacement of pipes, which are essential tasks. Performing maintenance tasks more frequently reduces the failure cost of the process by enhancing the process safety and reliability, but this leads to increased costs of inspection and replacement. Therefore, there is an optimal point that minimizes the total maintenance cost (including inspection, replacement, and failure) while satisfying the minimum safety level limit.
The objective of this study is to determine the optimal planning by changing and adjusting maintenance variables such as the initial pipe wall thickness, the number of inspections, and the inspection time. The first step in achieving this goal is the development of a probabilistic model that calculates the total maintenance cost as a function of the remaining pipe wall thickness with the first order reliability method. The remaining wall thickness is decreased by corrosion over time, which affects the total cost. The next step is to minimize the total maintenance cost of the model. A mixed integer nonlinear programming (MINLP) algorithm was employed to perform the optimization. The optimal inspection time, number of inspections, and the initial wall thickness were determined for various corrosion rates. A periodic inspection case that had the same time interval between inspections was also studied.

## 1. Introduction

In process industries such as refinery and petrochemical industries, most processes have regular shut-downs during which their pipes and equipment are inspected and replaced where necessary. A refinery plant's typical operating cycle is from three to four years, depending on the reliability of the processes and/or related laws and regulations. In this situation, refinery plants have faced an inevitable problem with determining the optimal inspection and replacement strategy that considers both safety and economy. It is certain that the frequent inspection and replacement of pipes enhances the safety of the process. However, too many inspections can greatly increase the maintenance cost while only slightly improving the process safety. Therefore, optimizing the inspection and replacement plan for pipes in the refinery process is an essential task due to the trade-off relationship between the process safety and the inspection efficiency.
One major threat factor in process safety is corrosion (Kim et al., 2011a), which weakens pipes and can eventually create unexpected failure, leading to substantial human, environmental, and economic loss. Therefore, many studies have been conducted to manage corrosion reactions in the literature Some studies analyzed the effects of corrosion factors to investigate corrosion mechanisms and others for developing corrosion rate forecasting models (Nesic, 2007). According to Nesic (2007), $CO_2$ corrosion is a major corrosion mechanism in oil and gas industries and the effects of pH, $CO_2$ partial pressure, temperature, flow, steel type, inhibition, condensation, and other factors on the corrosion rate have been experimentally examined in the literature. Electrochemistry and transport models have been developed to represent these experimental results. However, these models have limitations in their implementation in a real refinery plant (Tak et al., 2016). Moreover, corrosion mechanisms are too complex to be understood. For example, adding a small amount of $H_2S$ (<50ppm) significantly reduces the corrosion rate compared to the $CO_2$ corrosion rate (Lee, 2004). Therefore, Tak et al. (2016) proposed a statistical corrosion model based on real plant operation data.

In a refinery plant, the top part of a crude unit distillation column (CDU) employs carbon steel unlike the bottom part, which uses Hastelloy steel (Kim et al., 2011a). Therefore, the CDU overhead part requires intensive corrosion management (Kim et al., 2011b). This study developed a planning model for the inspection and replacement of pipes in terms of cost as a corrosion management method for the CDU overhead. Various cases were studied based on the developed cost model to determine the optimal inspection plan with pipe selection under different corrosion rates and inspection time interval strategies to minimize the total cost.

## 2. Model Description

The purpose of planning is to minimize the total cost. The cost in the model consists of the design, inspection, replacement, and failure costs.

$$\text{min.} \quad C_T = C_D + C_I + C_R + C_F \tag{1}$$

where $C_T$, $C_D$, $C_I$, $C_R$, and $C_F$ are respectively the total, design, inspection, replacement, and failure costs. The design cost is determined based on the pipe selection. The other costs are calculated as shown in Eqs (2)–(4).

$$C_I = \sum_{i=1}^{N} \frac{C_i}{(1+r)^{T_i}} \tag{2}$$

$$C_R = \sum_{i=1}^{N} \frac{C_r PR_i}{(1+r)^{T_i}} \tag{3}$$

$$C_F = \sum_{i=1}^{N+1} \frac{C_f (PF_i - PF_{i-1})}{(1+r)^{T_i}} \tag{4}$$

where $N$, $r$, $T_i$, $C_i$, $C_r$, $C_f$, $PR$, and $PF$ are respectively the number of inspections, interest rate, time of $i^{th}$ inspection, inspection cost factor, replacement cost factor, failure cost factor, replacement probability, and failure probability.

As shown in Figures 1 and 2, corrosion reactions at the top part of the CDU affect all costs by reducing the remaining pipe wall thickness: (1) A cheaper and thinner pipe increases both the failure cost and replacement cost, (2) corrosion enforces frequent inspection, and (3) an expensive and thicker pipe should be employed to ameliorate severe corrosion. Among these costs, replacement and failure costs are directly affected by the remaining wall thickness.

$$t_r(T) = t - V_{cr} X_g \mathrm{T} \tag{5}$$

where $t_r$, $t$, $V_{cr}$, $X_g$, and $T$ are respectively the remaining wall thickness, initial wall thickness, corrosion rate, uncertainty for grooving corrosion, and time. Replacement and failure margins are defined based on the

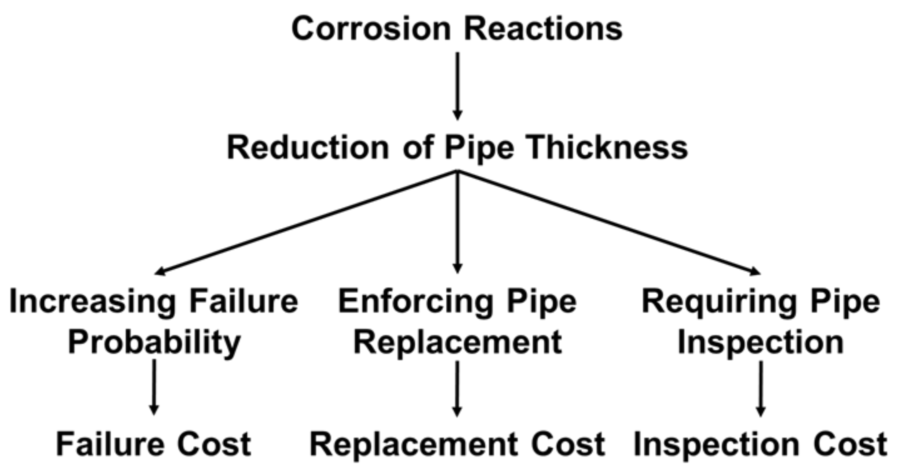


*Figure 1: Costs affected by corrosion reactions*

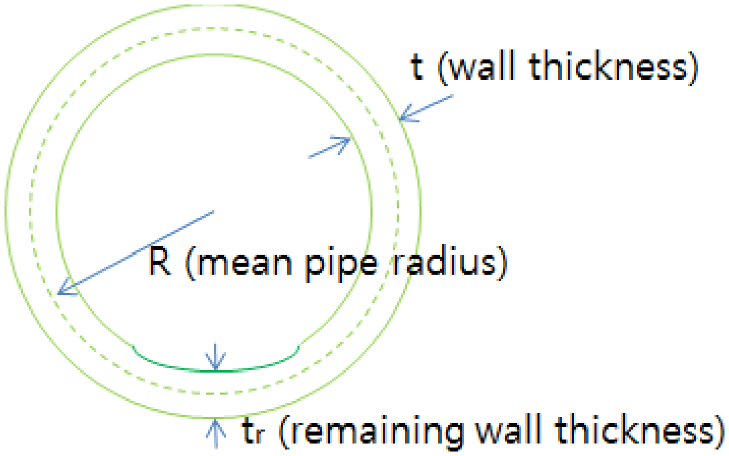


*Figure 2: Geometry of corroded pipe*

remaining thickness. The former is to determine whether pipe replacement is needed, and the latter is to check whether the pipe is approaching its bursting condition.

$$M_R(T) = t_r(T) - (t_{min} + \varepsilon) \quad (6)$$

$$M_F(T) = p_{bc}(T)X_{bc} - p_{opr}X_{opr} \quad (7)$$

where $M_R$, $M_F$, $t_{min}$, $\varepsilon$, $p_{bc}$, $X_{bc}$, $p_{opr}$, and $X_{opr}$ are respectively the replacement margin, failure margin, minimum allowable wall thickness, measurement error, bursting pressure capacity, uncertainty for bursting pressure capacity, operation pressure, annual maximum operation pressure ratio. The minimum wall thickness and bursting pressure capacity can be calculated according to ASME B31.3 code (2009) and Stewart et al. (1994)

$$t_{min} = \frac{pD}{2(SE+pY)} \quad (8)$$

$$p_{bc}(T) = k^{n+1}(\frac{1}{1+\varphi})^n \sigma_{uts}\frac{t_r(T)}{R} \quad (9)$$

where $p$, $D$, $S$, $E$, $Y$, $k$, $n$, $\varphi$, $\sigma_{uts}$, and $R$ are respectively the design pressure, pipe diameter, allowable stress, quality factor, stress-temperature compensating factor, yield criterion constant, hardening index, corroded fraction, ultimate tensile strength, and pipe radius.
Thus, the replacement and failure probabilities can respectively be obtained in terms of the replacement and failure margins.

$$\mathrm{PR(T)} = \mathrm{P}(M_R(\mathrm{T}) \le 0) \quad (10)$$

$$\mathrm{PF(T)} = \mathrm{P}(M_F(\mathrm{T}) \le 0) \quad (11)$$

## 3. Case Study

### 3.1 Case description

The developed planning model was applied to a refinery plant as a practical example. The target CDU treated 150,000 barrels per day (BPD). Since the overhead corrosion was the most severe in the CDU, the inspection and replacement planning focused on the top part. The pipe in the top part considered in this study was API 5L Grade X42 steel. Two constraints were assumed in the case study: the maximum pipe lifespan and the maximum allowable failure probability.

$$\mathrm{T} \le 20 \quad (12)$$

$$\mathrm{PF(T)} \le 10^{-4} \quad (13)$$

*Table 1: Design basis*

| Variable | Description (unit) | μ (expected value) | σ (standard deviation) |
|---|---|---|---|
| $r$ | Interest rate | 0.04 | |
| $V_{cr}$ | Corrosion rate (mm/year) | 0.5 / 1 / 1.5 | |
| $X_g$ | Model uncertainty grooving corrosion | 0.4 | 80% |
| $\varepsilon$ | Measurement error (mm) | 0 | 0.5 |
| $X_{bc}$ | Model uncertainty bursting capacity | 1.07 | 10% |
| $p_{opr}$ | Operation pressure (bar) | 1.8 | |
| $X_{opr}$ | Annual maximum operation pressure ratio | 1.1 | 5% |
| $p$ | Design pressure (bar) | 2.2 | |
| $D$ | Pipe diameter (mm) | 610 | |
| $S$ | Allowable stress (MPa) | 138 | |
| $E$ | Quality factor | 1 | |
| $Y$ | Stress-temperature compensating factor | 0.4 | |
| $k$ | Yield criterion constant | 1 | |
| $n$ | Hardening index | 0.16 | 5% |
| $\varphi$ | Fraction of corroded circumference (%) | 20 | 10 |
| $\sigma_{uts}$ | Ultimate tensile strength (MPa) | 414 | 4% |

The inspection and replacement planning problem was solved by a global optimization algorithm called a genetic algorithm (GA) in Matlab. GA is commonly used for nonlinear programming problems as a global optimization solver. Some studies in the literature have adopted it for mixed integer nonlinear programming (MINLP) problems such as heat exchanger network synthesis. Moreover, Matlab recently provided GA as an MINLP solver in its global optimization toolbox. The first order reliability method is applied to calculate replacement and failure probabilities. Table 1 shows the design basis used in this case study; as shown, the case study considers three different corrosion rates.

The three types of variable shown in Table 2 are adjusted as decision variables to determine the cost of the optimally planned refinery process: pipe selection (initial wall thickness), number of inspections, and inspection time. According to API 5L (2004), there are several available wall thicknesses for 610 mm pipes (X42 grade). Among these, wall thicknesses of 8.7, 10.3, and 11.9 mm are selected for the case study. Therefore, the variable for the pipe selection is an integer, as is the variable for the number of inspections. In the case of the inspection time, several variables apply based on the number of inspections. For example, when the number of inspections is one (N=1), there is only one inspection time variable ($T_1$). Meanwhile, three inspections (N=3) requires variables of first, second, and third inspection times ($T_1$, $T_2$, and $T_3$). Since the inspection number is an integer variable, four variables were assigned for the inspection time variables. Then, some of the variables were treated as slack variables based on the number of inspections.

Table 3 shows the cost information for the case study. The design cost and replacement factor depend on the pipe wall thickness. However, inspection and failure factors are the same regardless of the thickness because the inspection method and effects of failure do not differ for different thicknesses.

*Table 2: Decision variables*

| Variable | Description (unit) | Option | Note |
|---|---|---|---|
| $t$ | Initial pipe wall thickness (mm) | 8.7/10.3/11.9 | Integer |
| $N$ | Number of inspections | 1/2/3/4 | Integer |
| $T_i$ | $i^{th}$ inspection time (year) | 0–20 | Continuous |

*Table 3: Cost information*

| Variable | Description | 8.7 mm | 10.3 mm | 11.9 mm |
|---|---|---|---|---|
| $C_D$ | Design cost | $10,500 | $12,000 | $13,500 |
| $C_i$ | Inspection factor | | $300 | |
| $C_r$ | Replacement factor | | 1.5*$C_D$ | |
| $C_f$ | Failure factor | | $10,000,000 | |

*Table 4: Result 1 - uneven time interval with different corrosion rate*

| Variable | 0.5 mm/year | 1 mm/year | 1.5 mm/year |
|---|---|---|---|
| Pipe thickness (mm) | 8.7 | 10.3 | 11.9 |
| Number of inspections | 2 | 3 | 4 |
| Inspection time (year) | | | |
| T1 | 7.1 | 4.7 | 3.8 |
| T2 | 12.4 | 9.4 | 7.6 |
| T3 | | 14.5 | 11.6 |
| T4 | | | 15.7 |
| Pipe lifespan (year) | 20 | 20 | 19.9 |
| Design cost ($) | 10,500 | 12,000 | 13,500 |
| Inspection cost ($) | 411 | 627 | 833 |
| Replacement cost ($) | 27 | 2,254 | 6,465 |
| Failure cost ($) | 10 | 328 | 562 |
| Total cost ($) | 10,948 | 15,209 | 21,360 |
| Annualized cost ($/year) | 547 | 760 | 1,071 |
| Maximum Failure Probability | 1.9E-6 | 6.4E-5 | 1.0E-4 |

### 3.2 Analysis of results

The optimal inspection and replacement planning results are in Table 4. According to the results, the selection of the thickest pipe and the most frequent inspection are required for the highest corrosion rate case to satisfy the failure probability constraint, leading to increased design and inspection costs. In spite of these actions in this case, the value of the maximum failure probability reaches its upper bound. Therefore, the failure cost in this case is also higher compared to the other corrosion rate cases. Moreover, this means that the pipe lifespan is not at its maximum value of 20 years. The replacement cost is significantly increased for the highest corrosion rate case because of the expensive replacement factor, frequent replacement check, and fast corrosion rate. In contrast, the lowest corrosion rate case leaves little room for optimization because the corrosion is not severe and the design cost dominates. In summary, all costs (design, inspection, replacement, and failure costs) are at their worst in the fastest corrosion case, showing almost double the total cost compared to the slowest corrosion case. Therefore, preventing and controlling the corrosion rate plays a key role in the maintenance of the process. These can be achieved by either adding corrosion inhibitors or adjusting operating conditions.

The results in Table 4 show that the intervals between inspections are very similar: approximately seven years for the 0.5 mm/year case, five years for the 1 mm/year case, and four years for the 1.5 mm/year case. Unlike with irregular inspections, regular inspections have the advantage of managing and planning the process. Therefore, evenly spaced time interval cases are also investigated; Table 5 shows these results.

*Table 5: Result 2 – even time interval with different corrosion rates*

| Variable | 0.5 mm/year | 1 mm/year | 1.5 mm/year |
|---|---|---|---|
| Pipe thickness (mm) | 8.7 | 10.3 | 11.9 |
| Number of inspections | 2 | 3 | 4 |
| Inspection time (year) | | | |
| T1 | 6.7 | 5.0 | 4.0 |
| T2 | 13.3 | 10.0 | 8.0 |
| T3 | | 15.0 | 12.0 |
| T4 | | | 16.0 |
| Pipe lifespan (year) | 20 | 20 | 20 |
| Design cost ($) | 10,500 | 12,000 | 13,500 |
| Inspection cost ($) | 409 | 616 | 823 |
| Replacement cost ($) | 55 | 2,519 | 6,718 |
| Failure cost ($) | 2 | 242 | 553 |
| Total cost ($) | 10,966 | 15,377 | 21,360 |
| Annualized cost ($/year) | 548 | 769 | 1,080 |
| Maximum Failure Probability | 3.8E-7 | 3.9E-5 | 8.6E-5 |

Compared to the results of the unevenly spaced time interval cases, the evenly spaced cases show similar results: The pipe selection and inspection numbers are the same. The total cost has increased, which mostly results from the raised replacement cost; however, the total cost differences are very small. Furthermore, the process safety is greatly improved in terms of the maximum failure probability. Consequently, the highest corrosion rate case with an even time interval can meet the upper bound of the pipe lifespan of 20 years without reaching the failure probability constraint of $10^{-4}$. Therefore, considering the advantage of regular inspection and the process safety, an even time interval case is a better option.

## 4. Conclusion

The aim of this study was to develop a cost-optimal inspection and replacement planning model with consideration of the corrosion rate. The cost model comprises the design, inspection, replacement, and failure cost. Through corrosion reactions, the pipe wall thickness of the target process becomes increasingly thinner. This causes higher replacement and failure probabilities. Therefore, it is important to select an appropriate pipe, inspection number, and inspection time to minimize the maintenance cost.

As an example, the developed model was applied to a refinery process. The top part of a CDU for 150,000 BPD was selected for the case study. The planning model was an MINLP problem: integer variables for the pipe wall thickness and an inspection number and continuous variables for the inspection times. A genetic algorithm, an MINLP solver, found optimal planning results under different corrosion rates. The results showed that preventing and controlling the corrosion rate were very important factors for maintenance of the equipment. Moreover, evenly spaced inspection time intervals could be a better option in terms of regular intervals and process safety, although this required a slightly higher cost.

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