Journal of Materials Exploration and Findings (JMEF)

Volume 1
Issue 1 *Introduction to Journal of Materials Exploration and Findings*

Article 3

8-15-2022

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Recommended Citation

Hartoyo, Fernanda; Fatriansyah, Jaka Fajar; Mas'ud, Imam Abdillah; Digita, Farhan Rama; Ovelia, Hanna; and Asral, Datu Rizal (2022) "The Optimization Of Failure Risk Estimation On The Uniform Corrosion Rate With A Non-Linear Function," *Journal of Materials Exploration and Findings (JMEF)*: Vol. 1: Iss. 1, Article 3.
DOI: 10.7454/jmef.v1i1.1001
Available at: https://scholarhub.ui.ac.id/jmef/vol1/iss1/3

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Cover Page Footnote

The authors are thankful to KEMDIKBUDDIKTI and UI, which granted a research fund Program Pendanaan Perancangan dan Pengembangan Purwarupa (P5) 2022 Nomor: PKS-140/UN2.INV/HKP.05/2022.

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The Optimization Of Failure Risk Estimation On The Uniform Corrosion Rate With A Non-Linear Function

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Abstract. *Failures in the oil and gas pipeline system are conditions that must be avoided and anticipated because the losses due to the failures can occur at a very high level. Internal corrosion is one of the significant causes of the failures in pipeline systems. In addition, this type of corrosion is due to the high content of carbon dioxide and other corrosive substances in crude oil and natural gas. Therefore, an optimal inspection scheduling system is required to prevent the possibility of pipeline failures due to corrosion and to avoid any overspending on the budget due to excessive inspection scheduling. Risk-based testing (RBI) is one of the best methods to define a test planning system by using an optimal risk assessment. In this article, a Monte Carlo random number generator is applied by using a huge number of random iterations to approximate the actual risk value of a pipeline system with a limited sample at the scene. The nonlinear corrosion rate function is used for comparison with the commonly used linear corrosion rate function based on ASTM G-16 95. Once a risk value is estimated, the value is monitored based on an assessment of the risk matrix for each corrosion rate function by using the RBI method. The results show that the nonlinear corrosion rate function provides a more accurate approach to estimating the actual risk value and ultimately leads to an optimal inspection planning system.*

Keyword: *Risk Based Inspection, Simulation, Monte Carlo, Uniform Corrosion, Pipeline*

INTRODUCTION

The reliability of the pipeline system is needed in every petroleum industry to prevent failures. Failures in the pipeline system occur due to the interaction between the metal pipe and its environment, which will result in corrosion [1]. to overcome corrosion found, the Risk-Based Inspection (RBI) method is in line with developments. RBI uses risk to prioritize and set patterns rather than inspections [2]. The industry with a large scale requires a long time and costs that are not cheap in implementing the inspection. The reliability of the pipeline system is needed in every petroleum industry to prevent any failures in the system. Failures in the pipeline system occur due to the interaction between the metal pipe and its environment, which will result in corrosion [1]. One of the methods used to calculate corrosion damage is risk-based inspection [3]. RBI uses risk to prioritize and define models rather than a test by performing risk analysis calculations based on specific probabilistic models of uncertainty in the system or using random variables, also known as the stochastic algorithm, by using a Monte Carlo random number generator. The development of risk-based inspection, monitoring, maintenance, and repair management has increased the system reliability and reduced the costs of asset maintenance. In addition, control based on this risk analysis uses these risk estimates to make recommendations on how, when, and how they should perform the asset maintenance. This risk manager uses the value of risk analysis to determine the decisions in planning the efforts in inspection and maintenance [4]. The uncertainty may be related to fluctuation-driven processes which occur infrequently [5, 6, 7, 8,9].

However as corrosion rate is approximated using a linear function, in the process, this can lead to overestimation and underestimation of the value of the risk, which can affect the company's loss if the risk value is considered to be lower than the actual risk value. For the non-linear corrosion rate functional model used, the estimated risk value generated can be closer to the actual conditions to increase the reliability by developing a less negative value rather than using a linear corrosion rate. Moreover, the estimated corrosion rate in the model becomes more accurate and efficient for test planning decisions if the negative value is low.

In this paper, we considered using a nonlinear corrosion rate function model to optimize risk estimation for uniforms. So far, there is no dedicated paper to discuss this topic. Our goal is to pioneer the use of nonlinear corrosion rate function models to obtain optimized risk assessments for inspection plans for oil and gas facilities.

MATERIALS AND METHODS

In optimation of the failures, risk estimation using Monte Carlo random number generator is required in RStudio® [10] for the iterate over random variables by using a normal distribution and plotting a graph of the distribution, and MATLAB® is used for assistance in calculating variable values in CoF analysis. Microsoft Excel from Microsoft is also used for modeling the thickness of data into a function of corrosion rate and performing statistical work on thickness data. The materials used in this research are pipe data such as pipe thickness resulting from inspection in one of the operations of the areas and API RBI 581 Document as standard in risk estimation based on inspection. Materials were used to acquire the pipe thickness data from an RBI detailed assessment project conducted for oil and gas production and processing units, which then originates into a corrosion rate function modeling. For the pipe, carbon steel API 5L X52 Standard with 22 m for diameters and 975 m of total length is used. Pipe thickness data were taken from 12 inspection points with the types of cylindrical pipe sections, T-shaped pipes (Tee), and elbow pipes, as shown in Figure 1.

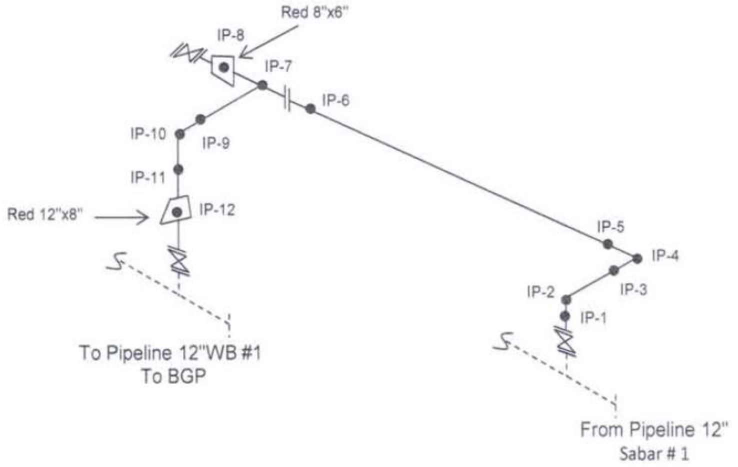


FIGURE 1. Map of inspection points in the pipe

Pipe thickness data is derived into two variations of the corrosion rate, including the linear and non-linear functions. This function variation is used to compare the corrosion rate functions according to the ASTM G-16 95 document regarding statistical data in the corrosion rate analysis. The linear corrosion rate is shown in equations (1) and (2).

$$m_f = m_i - CR.T \tag{1}$$

$$t_f = t_i - CR.T \tag{2}$$

The value of the corrosion rate, CR, was obtained as the independent variable. Meanwhile, the non-linear corrosion rate is shown in equations (3) and (4):

$$m_f = m_i - kT^b \tag{3}$$

$$t_f = t_i - kT^b \tag{4}$$

There are two independent variables in the equation: the value of the exponential constant, b, and the value of the mass loss coefficient, k. The results of the average and standard deviation of corrosion rate variations at all inspection iteration points are at least 100,000 times to produce the estimates that are close to the actual conditions by using Rstudio software to create the Art parameter value. The area value under the iteration curve is above the corresponding corrosion allowance value. It has been prepared in advance by using the standard weights adjusted Art to calculate the PoF (Probability of failure). PoF is then used to calculate the risk value, which can be used as a decision-making tool for planning further inspections or maintenance. In this study, a risk analysis uses the RBI method. RBI is a method that uses risk as the basis for conducting an inspection. In this study, RBI focuses on pipeline inspection, particularly the risk of failures due to uniform corrosion. The risk-based pipeline inspection system in this study utilizes the Monte Carlo simulation method to increase the accuracy in estimating the risk of gas pipeline failures due to uniform corrosion.

RESULTS AND DISCUSSION

Probability of Failure Value with Corrosion Rate Using Linear Equation

In calculating the A_{rt} parameter value on the corrosion rate of pipe thickness data, the corrosion rate value is calculated by using the data analysis function in Microsoft Excel. The inspection is carried out at 12 inspection points with different thicknesses. The data on the loss of thickness due to corrosion from each inspection point were taken as the average, and the standard deviation as input in the Monte Carlo random number generator was carried out on the RStudio application. The regression results from the pipe thickness data produce an average thickness loss per year. The modelling results show that the area in the area of evaluation is considered a failure event. The area to the left of x_1 is a value that is impossible to obtain in the process of losing thickness in the pipe because the value is negative, which is then shown in red in **Figure 2**. In contrast, the area to the right of x_2 is an evaluation value considered a failure event because the value exceeds the threshold of 0.2 or 20% of pipe thickness loss each year, shown in orange.

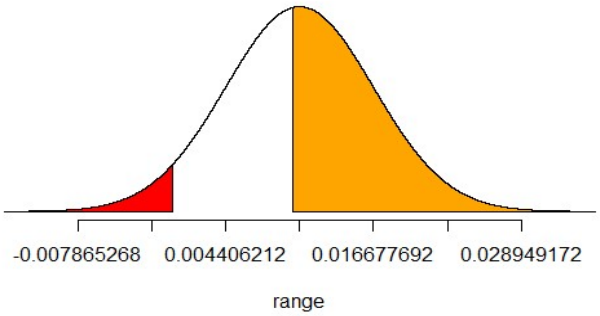


FIGURE 2. Monte Carlo simulation graph plot for Linear Equation Function on Corrosion Rate of PT. X.

Iterations generated from this Monte Carlo random number generator are 4,908,592 random value elements. The number of elements of this random value is very high. The value is close to the actual situation [10]. Therefore, the value of 0.4923045 is the Art parameter value. The value of the Art parameter that is then used in calculating the value of the damage factor, Df (t), uses the total five inspection data and the effectiveness value of "B" on the inspection to obtain the probability of failure (PoF) value. The value of the damage factor, D_f (t), is obtained at 36.9218 with a probability of failure value, $P_f(t)$, for the linear equation function in determining the corrosion rate of pipes using Monte Carlo simulations is 0.00110106.

Probability of Failure Value with Corrosion Rate Using Non-Linear Equation

Calculation of probability of failure with non-linear equation is calculated based on equation below

$$t_f = t_i - kT^b \tag{5}$$

t_f is final thickness of the pipe, t_i is the initial thickness of the pipe, k coefficient of mass loss and b is the constant of the exponent b. In this equation, linear regression is used to obtain the model and to produce the values of k and b as independent variables that can minimize the variance of the corrosion rate function.

$$log\ log\ \left(t_f - t_i\right)_n \ = log\ log\ k + b\ log\ T \tag{6}$$

when $a = log\ log\ k$, $b = b$, $y = log\ log\ \left(t_f - t_i\right)_n$, $x = log\ T$, $\left(t_f - t_i\right)_n$ is losing thickness for non-linear function model.

Based on the results of the data analysis function in Microsoft Excel for pipes, the average missing mass coefficient, k, is 0.017838682 and the standard deviation is 0.007436479. Then, the average value of the exponential constant, b, is 1.161959709, and the standard deviation is 0, 353666518. With the two mean values and the standard deviation of the variables, those can be used as variables that will also be used as random values by using Monte Carlo random number generator.

A. Calculation of the PoF Value by Using the Independent Variables of Exponent Constants, b.

In the first Monte Carlo random number generator for the non-linear corrosion rate equation function, the variable used as a random value is the value of the exponential constant, b, by setting the average loss coefficient value, k, as a fixed variable. Determination of the value used as a limit that determines the value in the iteration as a failure event is determined by entering the average value of the missing mass coefficient, k,. And, time, T, 20 years the value of$t_f - t_i$ is equal to 0.2, and k is equal to 0, 017838682 in equation 5. Our model uses the normal distribution as a random number generator. The area to the left of x_1 in this simulation does not mean anything because the value of the exponential constant may form a negative value and still form a valid equation. Meanwhile, the area to the right of x_2 is the evaluation value considered a failure event because the value exceeds the corrosion allowance value threshold, which is shown in red in **Figure 3.**

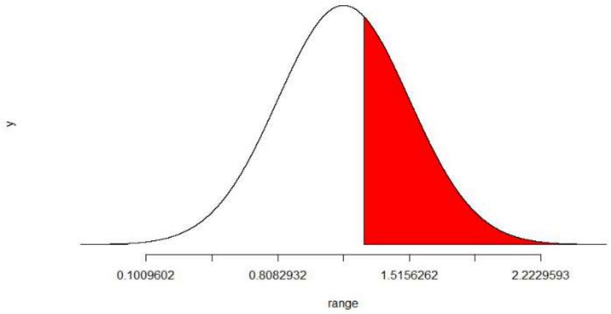


FIGURE 3. Model graph plot for Non-Linear Equation Function with constant value, b, as independent variable on Pipe Corrosion Rate

Based on **Figure 3,** the area to the right of the x_2 value has a value of 0.3799696 or 37.99696% of the iteration data and has a value above the threshold 1.269553525 as a corrosion allowance in the model analysis of non-linear corrosion rate with an independent variable value of exponential constant, b. Iterations generated from this model are 2,829,333 elements of random value. This number of random value elements is the goal of the our model because, with this number of iterations, the value shown will approach the actual situation [10]. Therefore, this value of 0.3799696 is used as the parameter value of A_{rt}. From the value of Art, the probability of failure value, $P_f(t)$, is used for a non-linear equation function with an exponential constant value, b, as an independent variable in determining the corrosion rate of pipes. PT. X of 2,5697x10^{-4}.

B. Calculation of PoF Value Using Independent Variable mass loss Coefficient, k.

In the first our model for the non-linear corrosion rate equation function, the variable to be used as a random value is the value of the exponential constant, b, by setting the average loss coefficient value, k, as a fixed variable. Determination of the value used as the limit that determines the value in the iteration as a failure event is determined by entering the average value of the missing mass coefficient, k, and, time, T, 20 years the value of $t_f - t_i$ is equal to 0.2, and b is equal to 1, 161959709 in equation 5. Our model uses the normal distribution as a random number generator. The modeling results show that the evaluation area is considered a failure event. The area to the left of x_1 is a value that is impossible to obtain in the process of losing thickness in the pipe because the value is negative, which is then shown in red in **Figure 4**. While the area to the right of x_2 is the evaluation value which is considered a failure event because the value exceeds the corrosion allowance value threshold, which is shown in **Figure 4.**

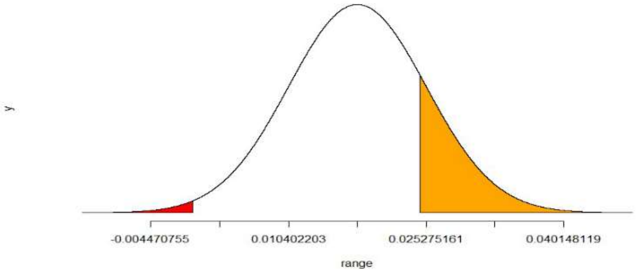


FIGURE 4. Model graph plot for Non-Linear Equation Function with missing mass coefficient value, k, as independent variable on Pipe Corrosion Rate

Based on **Figure 4,** the area to the left of the x_1 value has a value of 0.008224278 or 0.8224278% of the total iteration data, which has a negative value which is impossible, that this iteration value is not used in the analysis. Meanwhile, the area to the right of the x2 value has a value of 0.1725713 or 17.25713% of the iteration data, having a value above the threshold of 0.02462326 as a corrosion allowance in the model analysis of non-linear corrosion rate with the independent variable coefficient value. Mass loss, k. Iterations generated from this model are 594,919 random value elements. This number of random value elements is the goal of our model because, with this number of iterations, the value shown will be close to the actual situation [11].Therefore, the value of 0.1725713 is used as the value of the Art parameter. From the art value, the probability of failure value, P_f (t), for the non-linear equation function with the missing mass coefficient value, k, as an independent variable in determining the pipe corrosion rate is 3.06x10^{-5}.

Calculation of Consequence of Failure

The calculation of consequences using level 1 analysis by matching the pipe environment data with the table shown in the API RP 581 document uses fluid phase data in the form of C_1-C_2, fluid characteristics, probability of flammable, and other probabilities. The calculation of this consequence is limited to the continuous leakage type. *Failure value* is the cost consequence associated with all types of component failure whose values are fixed for linear and non-linear equations. From the calculation of CoF obtaining the value of financial consequences, the total value of financial consequences is calculated using equation, below.

$$FC = FC_{cmd} + FC_{affa} + FC_{prod} + FC_{inj} + FC_{envir} \qquad (7)$$

FC is the final financial consequence ($), FC_{affa} is the financial consequence of damage to surrounding equipment on the unit ($), FC_{cmd} is the financial consequence of component damage, $, FC_{inj} is the financial consequence as a result of serious injury to personnel ($), FC_{prod} is the financial consequence of lost production on the unit ($),

$FC_{environ}$ is the financial consequence of environmental clean-up ($). The result of calculating the value of financial consequences, FC, has a value of 1,023,894,651USD.

Risk Analysis using thickness of pipe

The equipment's risk value is calculated using a function of time equation, as follows:

$$\text{Risk} = \text{Probability of failure x consequence of failure} \tag{8}$$

In its calculation, the risk value combines the probability of failure value and the consequence value of the failure. The probability of failure is a function of time which means that the probability value will increase with increasing usage of time due to thinning or other damage mechanisms [12]. while for the value of the consequences of failure, the value does not depend on time. The probability of failure of the thickness data is calculated by using linear and non-linear corrosion rates. Furthermore, the consequences of failure value in terms of financing are then used to calculate the risk value, risk position in the risk matrix, and recommendations for further inspection planning based on the value and position in the risk matrix.

Risk Matrix and Risk Value

The risk matrix effectively shows the level of risk possessed by the inspected component shown in **Figure 5**. The probability of failure category is determined by the value of the damage factor, Df, while the probability category is determined by the magnitude of the financial consequences on the inspected pipe. The categories of probability and consequences of these failures are determined using **Table 1.**

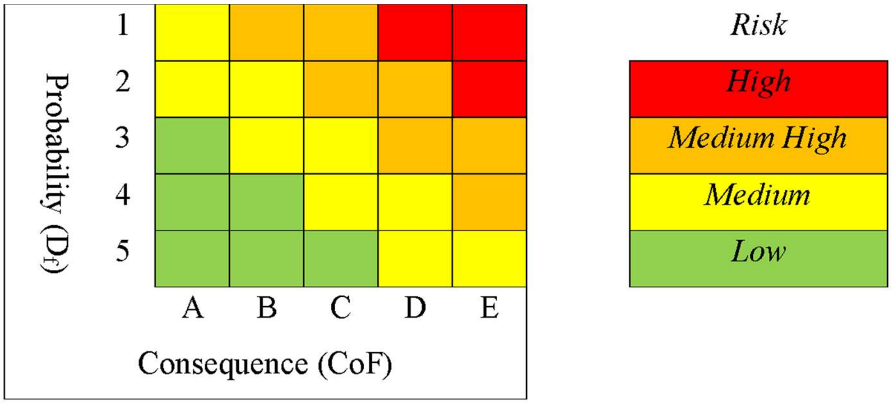


FIGURE 5. The risk matrix in RBI API Calculation.

TABLE 1. Numerical Values Associated with Probability and Area-Based Consequence Categories in API RBI [12]

Probability Category		**Consequence Category**	
Category	***Range***	**Category**	***Range* (USD)**
1	$D_f \leq 2$	A	$FC \leq 10.000$
2	$2 < D_f \leq 20$	B	$10.000 < FC \leq 100.000$
3	$20 < D_f \leq 100$	C	$100.000 < FC \leq 1.000.000$
4	$100 < D_f \leq 1.000$	D	$1.000.000 < FC \leq 10.000.000$
5	$D_f \geq 1000$	E	$FC \geq 10.000.000$

Table 1. Shows model results of corrosion rate data on pipes. It is found that the model on the linear corrosion rate equation function gets probability in the category 3. The model on the non-linear corrosion rate equation function with

the value of the exponential constant, b, as the independent variable gets probability in the category 2, and for the model on the non-linear corrosion rate equation function with the missing mass coefficient value, k, as the independent variable gets probability in the category 1. The consequence category value is fixed and the same because inspections are carried out at one time. The components are the same, the differences are only for the corrosion rate function used and the independent variables used in the models. The results of the risk definition assessment on the risk matrix and the effect of changing the type of equation function in this study are shown in **Figure 6.**

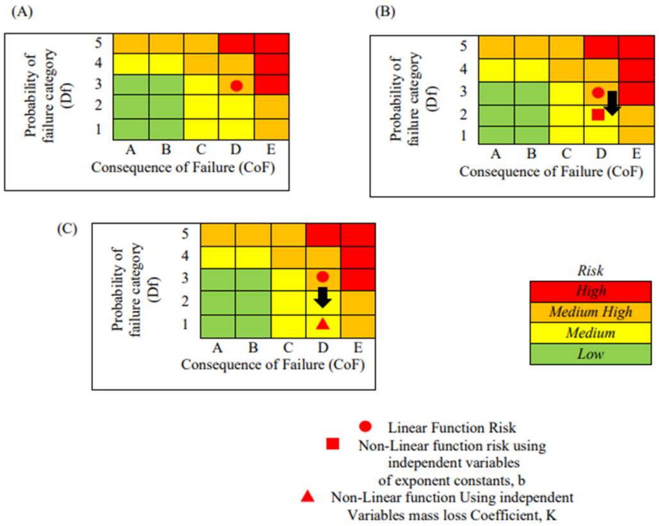


FIGURE 6. Risk value based on risk matrix API, A) Risk value in Linier equation, B) effect of different risk value at non-linear equation with exponential constant, *b*, as an independent variable, C) effect of different risk value at non-linear equation with mass loss, *k*, as an independent variable.

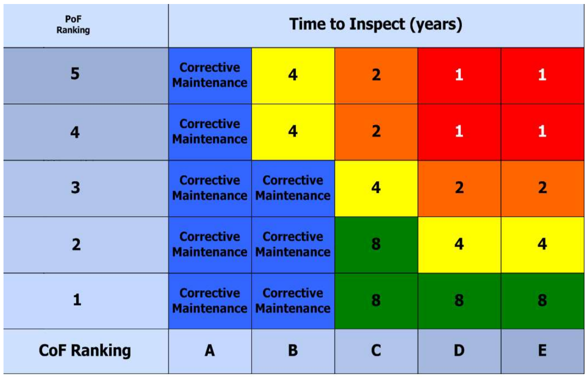
The results in **Figure 6.** show that the linear corrosion rate equation has a higher risk definition than the non-linear corrosion rate. The linear corrosion rate equation show a higher or overestimated risk value than the risk value indicated by the non-linear corrosion rate equation. The calculation results of the risk value are shown in **Table 2**. The risk value in the linear corrosion rate equation function occupies the highest risk compared to the non-linear corrosion rate equation function, using the exponential constant value, b, or using the missing mass coefficient value, k, as the independent variable. These results prove that there is a decrease in value or a reduction of 77.25% for the use of non-linear corrosion rates using the value of the exponential constant, b, as the independent variable, and 97.29% for the use of non-linear corrosion rates using the value of the missing mass coefficient, k, as the independent variable in the iteration of the Monte Carlo random number generator. These results can influence the factory management's decision making for further inspection activities. The use of a non-linear corrosion rate function model is proven to provide more accurate results than a linear corrosion rate function which is commonly used in corrosion rate function modelling.

TABLE 2. the result of risk value in pipe's data based on independent variable and corrosion rate function equation.

No	Corrosion rate function	Independent variable	PoF	*FC* (USD)	Risk value (USD)	Reduction of risk (%)
1	Linier	CR	0,0011298	1.023.894,651	1.156,8	0
2	Non-Linier	*b*	$2{,}5697\times10^{-4}$	1.023.894,651	263,11	77,25
3	Non-Linier	*k*	$3{,}06\times10^{-5}$	1.023.894,651	31,33	97,29

Inspection planning

Inspection planning is essential in industries such as natural gas and oil processing due to the industry's high risk and high-cost nature. The inspection process is also an activity that costs very high, and inspection planning must be carried out optimally as the costs incurred are right on target and efficient. One of the methods given in the API RP 581 document in planning the next inspection is to implement a risk value target. This risk target value can be used to limit the result that if the projected risk value increases with time, the risk probability value increases with increasing time as the next inspection is carried out before. Or, it is suitable when the risk value reaches the predetermined risk target value. Planning for further inspections can also be carried out with a simple method of calculating time by using a risk matrix. In **Figure 7**, the minimum time for planning the next inspection can be known in the risk matrix.



PoF Ranking	Time to Inspect (years)				
5	Corrective Maintenance	4	2	1	1
4	Corrective Maintenance	4	2	1	1
3	Corrective Maintenance	Corrective Maintenance	4	2	2
2	Corrective Maintenance	Corrective Maintenance	8	4	4
1	Corrective Maintenance	Corrective Maintenance	8	8	8
CoF Ranking	A	B	C	D	E

FIGURE 7. Modified risk matrix to determine the time of the next inspection.

Based on **Figure 7.**, for the 3 models, the data on the corrosion rate of the pipe is obtained in model on the linear corrosion rate equation function. The time required for the next inspection is two years. In contrast, for the model on the non-linear corrosion rate equation function with a value of the exponent constant, b, and the missing mass coefficient value, k, as independent variables still have four years and eight years for an inspection time. The inspection plans for 3 models of corrosion rate data on pipes are shown in **Table 3**. From the results of planning the next inspection time, using the linear corrosion rate function will be detrimental to the user because the time is 2 to 4 times faster than the non-linear corrosion rate function, so the cost for inspection becomes excessive and inefficient. This proves that using non-linear equations to estimate the corrosion rate using our model can reduce the costs incurred for inspection activities by 50% to 75% compared to inspection costs using the linear corrosion rate function.

TABLE 3. The results of calculating the percent reduction in inspection costs for each type of variable in the model test

No	Corrosion rate function	Independent variable	Probability category	Consequence category	The next inspection time (year)	Inspection cost in 20 years (USD)	Percent reduction of inspection cost (%)
1	Linier	CR	3	D	2	314.105,4	0
2	Non-Linier	*b*	2	D	4	157.052,7	50
3	Non-Linier	*k*	1	D	8	78.526,35	75

SUMMARY

We have successfully build model in the Risk-Based Inspection method (RBI) linear and non-linear function of corrosion rates. The risk value in the linear corrosion rate function has a higher risk value than the non-linear function of corrosion rate. We have found that the non-linear corrosion rate function model is proven to reduce the percentage of negative values in the independent variable iteration. The percentage of negative values causes inaccuracies in the risk assessment process compared to the linear corrosion rate model. The percentage of negative values indicated by the corrosion rate function non-linearity is 0.8224278 % with a decrease in iteration up to 3.4662872%, which can increase the level of accuracy of the model.

ACKNOWLEDGMENTS

The authors are thankful to KEMDIKBUDDIKTI and UI, which granted a research fund *Program Pendanaan Perancangan dan Pengembangan Purwarupa (P5) 2022 Nomor: PKS-140/UN2.INV/HKP.05/2022.*

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