Prediction of residual life for oil and gas pipe with local corroded defects

Wenhe Wang\textsuperscript{a,b*}, Jun Yi\textsuperscript{a,b}, Tieming Liu\textsuperscript{c}

\textsuperscript{a}College of Safety Engineering, Chongqing University of Science & Technology, Chongqing 401331, China
\textsuperscript{b}Chongqing Academy of Safety Science and Technology, Chongqing 401331, China
\textsuperscript{c}China Academy of Safety Science and Technology, Beijing 100012, China

Abstract

According to the corrosion failure characteristics of buried oil and gas pipelines, electrochemical corrosion rates of the local corrosion and pitting corrosion flaws were derived by Faraday's laws, and the limit size model of corrosion defects was established based upon ASME-B31G criteria. A new method of the residual life prediction for buried pipelines was finally developed based on the corrosion rate model and limit size model of corrosion defects, and the prediction method was validated with an example and the results showed that the method is reliable for pipelines with corroded defects.

Keywords: Residual life; Corroded pipelines; Electrochemical model; Life prediction

1. Introduction

Some researchers and institutes have carried on many studies on residual life prediction of corroded pipeline presently. The criterion RP0502-2002 on Pipeline External Corrosion Direct Assessment Methodology proposed by National Association and Corrosion Engineer (NACE) is conservative based on assumption of typical corrosion flaws shape; methods used to analysis corroded life based on empirical value formula and statistics of extreme values, which need much historical inspection data of pipeline, and the results of residual life are aim at total pipeline but not a corroded point; because of the shortage of operationality and complexity in the process of judgment, the results computed by life prediction model

* Corresponding author. Tel.: +0-086-023-65023116; fax: +0-086-023-65023099.
E-mail address: wangwenhe518@163.com.
of pipeline based on Artificial Neural Networks (ANN) need to improve further [1-4]. Above these factors on prediction models are limited to apply on-site place, while life prediction model of pipeline based on electrochemical theory is a perfect one relied on once inspection data, which parameters data influenced on electrochemical corrosion rate can be obtained in-site place easily, so the model is regard as an important one in application and is more attention increasingly.

Corrosion defect shapes can be divided into general corrosion, local corrosion and pitting corrosion according to corrosion failure characters shown as Fig.1. Because of the protection of coatings, the big area general corrosion situation of pipelines is few, while two kinds of corrosion shape as local corrosion and pitting corrosion shape in the damaged defects between substrate and coating of pipelines exit usually [5]. According to electrochemistry theory, there is a quantitative relationship between corrosion current and pipe metal loss. So the model of corrosion rates, which can determine relationships between length and depth size of corrosion defects, between corrosion rates and depth size of corrosion defects and times, were established for local corrosion and pitting corrosion defects in the development of corrosion.

In the paper, according to corrosion failure characters of buried oil and gas pipelines, electrochemical corrosion rates of the local corrosion and pitting corrosion flaws were derived by Faraday’s Law, and the limit size model of corrosion defects was established based upon ASME-B31G criteria. A new method of the residual life prediction for buried pipelines was finally developed based on the corrosion rate model and limit size model of corrosion defects, and the prediction method was validated with an example and the results showed that the method is reliable for pipelines with corroded defects.

2. Limit pressure and size of corrode pipeline

2.1. Limit failure pressure of corrode pipeline

Limit failure pressure is the limit pressure in the pipeline as failed. The formula of limit failure pressure of pipeline with corrode defects based upon ASME-B31G criteria can be obtained as follows [1]:

\[
P = \sigma_f \left( \frac{2t}{D} \right) \left[ \frac{1 - h/t}{1 - h/\tau M^{-1}} \right]
\]

But the maximum allowable working pressure predicted based on ASME-B31G criteria is more conservative, so in order to removing or eliminating the shortage, Folias factor \( M \) and yield limit of pipe materials \( \sigma_f \) were improved as follows [6-8]:

\[
M = \sqrt{1 + 0.6275 \left( \frac{l}{\sqrt{Dt}} \right)^2 - 0.003375 \left( \frac{l}{\sqrt{Dt}} \right)^4} \quad \left( \frac{l}{\sqrt{Dt}} \right)^2 \leq 50
\]

\[
M = 0.032 \left( \frac{l}{\sqrt{Dt}} \right)^2 = 3.3 \quad \left( \frac{l}{\sqrt{Dt}} \right)^2 > 50
\]
\[ \sigma_f = (\sigma_s + 68.95) \]  \hspace{1cm} (4)

Where \( P \) is failure pressure of corroded pipeline, \( D, t, h \) and \( l \) are outer diameter and wall thickness of pipelines, length and depth of corrosion defects respectively, \( \sigma_f \) is flow stress.

2.2. Maximum allowable corrosion depth of pipe wall

Defect sizes of corroded pipeline are critical sizes while limit failure pressure equals to inner pressure of pipeline, then formula (1) can be shown as follow (5):

\[ P_L = \sigma_f \left[ \frac{2t}{D} \left( 1 - \frac{h_{\text{max}}}{tM^{-1}} \right) \right] \]  \hspace{1cm} (5)

Where \( h_{\text{max}} \) and \( P_L \) are the maximum allowable corrosion depth of pipe wall and inner pressure of pipeline respectively. The corrosion defects changed in the direction of both the depth and length with time, so Folias factor \( M \) changed in the corrosion process.

3. Corrosion rate of pipeline

3.1. Model of local corrosion based on electrochemical theory

Local corrosion surface can be founded as oval, parabola shape in depth direction based on local-corrosion’s characters, meanwhile, the growth course of its surface corrosion defects is assumed that the defects grows proportionally in length, width and depth three directions[9-10], it can be shown as Fig.2:

![Fig.2. Model of Geometry shape for local corrosion defects](image)

Where \( a \) and \( b \) separately are the semi-length of long axis and short axis of elliptic, \( h \) is the depth of corrosion defects, \( C_1 = 2a/h, C_2 = a/b \), then \( a = C_1 h/2 \), \( b = a/C_2 = C_1 h/2C_2 \). According to geometric shape, micro-loss of pipeline metal and its the differential form can be expressed as follows:

\[ dM_v = \rho \times dV = \rho \pi \left( \frac{3C_1^2}{4C_2} + 1 \right) h^2 dh \]  \hspace{1cm} (6)

\[ dM = kI dT \]  \hspace{1cm} (7)

Where \( dM \) is micro-loss of pipe metal, \( dT \) is micro-time segment, \( I \) is corrosion current, \( k \) is electrochemical coefficient, \( k = A/FU \), \( A \) and \( U \) are separately atomic weight and valence of iron, \( F \) is...
faraday constant and $F=96500 \text{C/mol}$, therefore the steel pipe's $k=1.042$. Equivalent corrosion current, resistance, and equivalent corrosion resistance can be obtained according to equivalent corrosion circuit of coating pipeline as follows:

$$I = \frac{\Delta V_h}{R_h}$$  \hspace{1cm} (8)

$$R_h = \frac{\xi h}{S}$$  \hspace{1cm} (9)

$$R_h = \frac{2\xi(3C_2 + 4C_2^2 / C_1^2)}{3\pi C_1^2 h}$$  \hspace{1cm} (10)

Where $\Delta V_h$ and $\xi$ are the potential differences against ground and of electrical resistivity of pipe respectively, $R_h$ and $S$ separately are equivalent resistance and surface area of corrosion defects. According to Faraday's law, the metal loss $M_I$ can be expressed, and $M_I=M_f$; so the local corrosion rate can be got as follows:

$$dM_I = k \frac{\Delta V_h}{R_h} dT = k \frac{3\Delta V_h \pi C_1^2}{2\xi(3C_2 + 4C_2^2 / C_1^2)} h dT$$  \hspace{1cm} (11)

$$\frac{dh}{dT} = \frac{12C_1^4 k \Delta V_h}{(3C_1^2 + 4C_2)(4C_2 + C_1^2) \xi \rho h}$$  \hspace{1cm} (12)

$$dT = \frac{12C_1^4 k \Delta V_h}{(3C_1^2 + 4C_2)(4C_2 + C_1^2) \xi \rho h} dh$$  \hspace{1cm} (13)

3.2. Model of pitting corrosion based on electrochemical theory

Pitting corrosion surface can be founded as elliptic, cone-shaped in depth direction and total defects shape is elliptic cone. Meanwhile, the growth course of its surface corrosion defects is assumed that the defects grows proportionally in length, width and depth three directions[9-10], it can be shown as Fig.3:

Where $d$, $h$ and $\alpha$ separately are the diameter of cone bottom, height of cone and semi-angle of the top cone, so the cone volume and micro-loss of pipeline metal can be expressed as shown:

$$V = \frac{1}{3} \pi \left(\frac{d}{2}\right)^2 h = \frac{1}{3} \pi \tan^2 \alpha h^3$$  \hspace{1cm} (14)
\[ dM_v = \rho dV = \pi \rho h^2 \tan^2 \alpha dh \]  

(15)

Equivalent corrosion circuit and micro-loss in the corrosion process for coating pipeline can be displayed as follows:

\[ I = \frac{2\pi \Delta V_h h}{\xi} \]  

(16)

\[ dM_I = k \frac{2\pi h \Delta V_h}{\xi} dT \]  

(17)

According to Faraday's law, the metal loss \( M_I \) can be expressed, and \( M_I = M_f \), pitting corrosion rate can be got as follows:

\[ \frac{dh}{dT} = \frac{2\cot^2 \alpha k \Delta V_h}{\xi \rho h} \]  

(18)

\[ dT = \frac{\xi \rho h \tan^2 \alpha}{2k \Delta V_h} dh \]  

(19)

4. Residual life prediction of corroded pipeline

4.1. Procedure of prediction

The Folias factor \( M \) should be determined by defect sizes at first, but corrosion defects are changing in the directions of depth and length in the process, so the Folias factor \( M \) is a variable determined by depth and length, and a program was written for computing the maximum allowable corrosion defects depth of pipe wall, the flow chart is shown in Fig.4, where \( K \) is ratio between corrosion defects initial axial length \( L_o \) and initial depth \( h_o \), \( \Delta t \) is step of defects depth, generally \( \Delta t = 0.001 \) mm, then the parameters of electrochemical and materials of pipeline were entered to compute the residual life prediction of corroded pipeline by integral aimed at corrosion models.

4.2. Example

A crude oil pipeline, which total length is 183km, material is 20# steel and design pressure is 6.28MPa, mostly soil is clayey along the pipeline, soil resistivity is lower between 30 and 60 \( \Omega \cdot m \), have occurred pipeline leakage cases during operation. Local corrosion and pitting corrosion defects were found in an inspection of the pipeline in May.2002, the pipeline with local corrosion defect occurred cracking after six years, and pitting corrosion defects developed and become the perforation less than one year (0.90 year). An example, predicting corrosion residual life against local corrosion and pitting corrosion based on corrosion defects data and pipeline, was displayed and basic parameters shown in Table 1, 2 and 3.

According to electrochemical corrosion models, the formulas of local corrosion and pitting corrosion pipelines with defects can be obtained as follows, and then parameters were input to computer the results of residual life of corroded pipeline, it is shown as Table 4. Thus, residual life prediction calculation based on the electrochemical model is simple, and the error is acceptable in engineering. These results indicated that models to predict the residual life of corroded pipelines is feasible and usability on-the spot.


\[ T = \frac{(3C_1^2 + 4C_2)(4C_2 + C_1^2) \rho \xi}{24C_1^4 k \Delta V_h} (h_{\text{max}}^2 - h_0^2) \]  

(20)

\[ T = \frac{\rho \xi}{16k \Delta V_h} (t^2 - h_o^2) \]  

(21)

Fig. 4. Flow chart of calculation for maximum allowable corrosion defects depth of pipelines

Table 1. Parameters of corrosion defects

| Pipeline | Local corrosion defect size (mm) | Pitting corrosion defect size (mm) |
|----------|----------------------------------|-----------------------------------|
|          | thickness | length | width | depth | diameter |
| Example  | 6.35      | 17     | 90    | 2.5   | 2.5      |

Table 2. Design parameters of pipeline

| Pipeline | Pressure (MPa) | Diameter (mm) | Thickness (mm) | Yield limit (MPa) | Poisson’s ratio | Design Conv. | Weld Conv. | Strength Conv. |
|----------|----------------|----------------|----------------|-------------------|-----------------|--------------|------------|---------------|
| Example  | 5.2            | 426            | 10             | 358               | 0.3             | 0.72         | 1          | 0.9           |
|          | 4.0            | 529            | 7              | 325               | 0.3             | 0.72         | 1          | 0.9           |

Table 3. Electrochemical parameters of corrosion

| Pipeline | Potential (V) | Resistivity (\(\Omega \cdot \text{m}\)) | Electrochemical constant (k) | Density of pipeline (g/cm³) |
|----------|--------------|----------------------------------------|-----------------------------|----------------------------|
| Example  | 0.216        | 51.2                                   | 1.042                       | 7.55                       |
|          | 0.20         | 90                                     | 1.042                       | 7.55                       |
Table 4. Results of forecasting for corrosion residual life

| Example    | Local corrosion | 6.79 | 6.0 | 13.16 |
|------------|-----------------|------|-----|-------|
| Pitting corrosion | 0.98 | 0.90 |     | 8.89  |

5. Conclusions

The corrosion defect sizes models were established based on corrosion characteristics of buried pipelines and on basics of the failure pressure equations from ASME-B31G criteria, and the residual life prediction models based on the electrochemical corrosion models were established for the local corrosion and pitting corrosion defects. The models can be used to predict specific defect points, and the required data are easily obtained by field detection without dependence on historical detection data. It is easier compared with the traditional forecasting methods and the results are reliable; it has certain applicability on local site.

The results predicted by corrosion residual life prediction models are basically consistent with the actual pipeline residual life based on corrosion inspection data and the error is less. So the models based on electrochemical theory have good effect on predicting residual life of corroded pipelines.

Acknowledgments

This work are supported by the Natrual Science Foundation of Chongqing Science and Technology Commission (CSTC,2010BB5283), the Key Technologies R & D Program Foundation of Chongqing Science and Technology Commission (CSTC,2010AC0186), the Key Technologies R & D Program Foundation of State Administration of Woke Safety (No.10-115), the Open Research Fund of Key Laboratory of Material Corrosion and Protection of Sichuan Colleges and Universities (2010CL02) and the Fund of Chongqing University of Science & Technology (CK2010B17).

References

[1] ASME-B31G:1991 Manual for Determining the Remaining Strength of Corroded Pipelines.[S].
[2] BS 7910:1999 Guide on Methods for Assessing the Acceptability of Flaws in Fusion Welded Structures[S].
[3] DNV2RP2101:1999 Corroded Pipeline[S].
[4] API RP-579:2000 Recommended Practice for Fitness-for-Service[S].
[5] CHENG Yuan-peng, BAI Yu, LI Xiao-yan, etal.Residual life prediction method of corroded buried oil pipeline [J]. Pressure Vessel Technology, 2009, 26(2),pp.30-34.
[6] Zhao J.Z.Fittness assessment of pipeline with defects[M].Beijing: China Petrochemical Press. 2005, pp.121-128.
[8] YU S.R, LI J.H, LI S.X. Probability model of corrosion residual life protection for buried pipeline [J]. Chinese journal of safety science, 2008, 18(6),pp.11-15.
[9] Dr Jane Haswell. The pipeline life cycle [J]. Pipes & Pipelines International, 2006, 44 (6), pp.24-34.
[10] David Batte, Bin Fu. Advanced methods for integrity assessment of corroded pipelines [J]. Pipes & Pipelines International, 2000, 42(4). pp.124-138.