Failure Analysis of Corroded API 5L X 46 Gas Pipeline

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Abstract: A gas API 5L X46 steel pipeline developed corrosion pits after 27 years in service leading to gas leakage. The pits were found to nucleate locally at the internal surface of the pipeline. The aim of the present study is to clarify the cause of corrosion failure using standard failure analysis techniques including visual examination, chemical and mechanical characterizations, metallurgical examinations using light optical microscopy, scanning electron microscopy (SEM) microanalysis equipped with energy dispersive X-ray (EDX) and corrosion test using a three-electrode potential technique. Results showed that natural gas inside the pipeline was identified to contain a small amount of steam and free condensed water formed as the temperature of the natural gas dropped below the water dew point. As a result, the internal surface of the pipeline was water wetted. Due to its high percentage of aggressive chloride ions (Cl^-), this water acted as electrolyte resulting in pitting corrosion which attacked locally. Such corrosion attack led to leakages in the pipeline. The mechanism of corrosion failure is proposed and some techniques for control of corrosion are recommended in the present investigation.

Keywords : Gas pipeline; pitting corrosion; chloride ions; corrosion control

1. Introduction

The increasing demand for energy, especially in industrialized countries has stimulated oil and gas companies to search for non-renewable energy, i.e. natural gas in remote places. As a result, an adequate infrastructure is required to carry natural gas from extraction fields to storage sites and from these facilities, gas flows to treatment plants and distribution facilities and finally, to urban and industrial consumption areas. Pipeline is the most economical and efficient means of large scale fluid transportation for natural gas compared to rail, truck and tanker transportation in term of the flexibility of routes and large quantities to be moved on.

Gas pipeline requires high level of safety, low cost, high operational efficiency and minimum accident. Carbon steels are generally used for gas pipeline due to some reasons, i.e. carbon steels have good mechanical properties, low cost and wider availability despite their corrosion resistance is relatively low [1,2]. The severity of corrosion depends on various working parameters such as corrosive agents (CO_2, H_2S, chloride), temperature, and surface films [3-5]. Combined effect of these corrosive agents and high flow velocity of gas promote the deterioration of the steel pipeline, mainly due to corrosion-erosion.

A gas API 5L X46 steel pipeline presented leakage after 27 years in service. Visual examination showed that leakages were caused by the formation of pits. Data on service conditions and material specification are given as follows

• Diameter	:	12.75 inch
• Wall Thickness	:	0.5 inch
• Year Built	:	June, 1981
• Material	:	ERW/API 5L X-46
• Operating Pressure	:	160 psi

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- Operating Temperature : 90 ^{o}F
- Fluid Service : Gas
- Production : 6 mmscf/day

2. Experimental Procedure

Standard failure analysis methods were carried out to investigate the cause of failure and these include visual examination, chemical and mechanical characterizations (hardness measurement and tensile test), metallurgical examinations using light optical microscopy, scanning electron microscopy (SEM) microanalysis equipped with energy dispersive X-ray (EDX) and corrosion test using a three-electrode potential technique.

3. Results

3.1. Visual examination

Fig.1 shows failed API 5L X46 gas pipeline which has been used for transporting gas for 27 years. It can be seen that corrosion attacks occurred locally, especially at the bottom of the pipeline (6 o’clock position). These corrosion pits were observed to cause leakage.

Figure 1. Failed pipeline

3.2. Chemical Composition of Pipeline Materials

The chemical composition of the pipeline and the corresponding standard API 5L X46 are given in Table 1. The main alloying elements specified by API 5L X46 are C, Mn with impurities of P and S. Referring to Table 1, it can be concluded that the pipeline composition is closely match with API 5L X46. Of note is that elements such as Cr and Cu are properly added to an alloy steel to improve its corrosion resistance.

3.3. Microstructural Analysis

Photomicrograph of the pipeline under study is shown in Fig.2. It can be seen that the microstructure for the pipeline is composed of ferrite (light etched) and pearlite (dark etched) which are elongated along a rolling direction known as texture as commonly seen in low carbon steels. Such microstructure can give high strength in steels via grain refinement according to Hall-Petch relationship.

Table 1. Chemical compositions of pipelines

MATERIAL	Yield Stress (MPa)	Ultimate Stress (MPa)	VHN
Pipeline	343.7	446.9	150.7
API 5L X46	317 min	434 min	-

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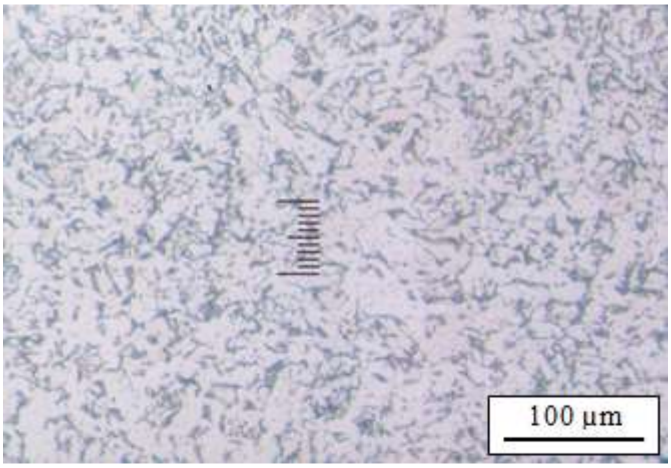

Figure 2. Microstructure of API 5L X46 steel

3.4. Tensile Strength and Hardness

Mechanical properties of the pipeline were assessed using tensile and hardness tests with the results are shown in Table 2. Based on yield and ultimate stresses, the pipeline may be categorized as API 5L X46 where minimum yield and ultimate stresses required are 317 and 434 MPa respectively. The measured hardness values of the pipeline is around 150.7 VHN with the yield stress to ultimate tensile stress ratio of 0.730 close to its standard API 5L X46. Referring to Table 2, it can be seen the strength of the pipeline is around 3 times higher than the hardness value hardness.
Table 2. Mechanical properties of the pipeline

3.5. Chemical Analysis of Water

Historical data showed that water was present in the gas pipeline. Chemical analysis of water was carried out using spectrophotometer UV-vis. Aggressive anions such as Cl^- was successfully detected with the results are given in Table 3. Water has a pH of 8.5 and this means that water is in basic condition.

Table 3. Chloride contents in the water phase

Material	Cl (ppm)	pH
Gas Pipeline	4985.4	8.5

Material	Chemical Compositions (wt%)												
	C	Mn	Si	P	S	Al	Nb	V	Ni	Cr	Ti	Mo	Cu
Pipeline	0.138	0.632	0.163	0.094	0.025	0.067	0.013	0.010	0.059	0.052	0.007	0.067	0.103
API 5L X46	0.29 Max	1.25 Max	0.35 Max	0.04 Max	0.05 Max	0.04	0.05	0.07	-	-	-	-	-

3.6. Chemical Analysis of Inner-Side Deposits

Fig.3(a),(b) show the surface profiles of the pipeline under study taken from the 6 o'clock position where the majority leaks occurred in these regions. It can be seen that the internal surface of the pipeline is suffered from erosion effect as shown in (a) whereas in Fig.b shows clearly corrosion pits. These corrosion pits could be responsible for the occurence of leakage in the gas pipeline.

Fig.4 shows SEM factographs of corrosion pits and corrosion products with EDX-spectra of the gas pipeline. As is seen, not many corrosion products forms on the surface. It seems that gas flow causes the erosion process and the scales or corrosion products are periodically scoured from the exposed surface.

EDX-spectra taken from corrosion products, i.e. region A in Fig.4b, is shown in Fig.4c. As is seen, these corrosion products are composed of mainly O and Fe which may be in the form of ferrous hydroxides, $Fe(OH)_2$ and/or ferric hydroxides, $Fe(OH)_3$. The presence of Cl suggests that FeOCl forms as a result of chloride attack on hydrated passive film (FeOOH). EDX-spectra taken from region marked B in Fig.4b show elements, mainly Si, O and Cl with the traces of Na, Mg, S and Ca as shown in (d). Silicon may be associated with silica (SiO_2) known as sand particles. The presence of sand can promote erosion and destroy passive film of pipeline steel.

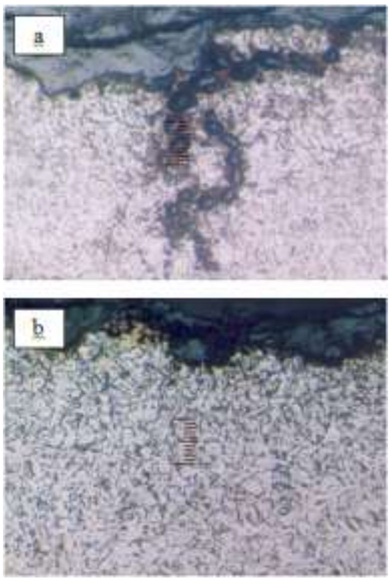

Figure 3. Surface profile : (a) along and (b) perpendicular to flow direction

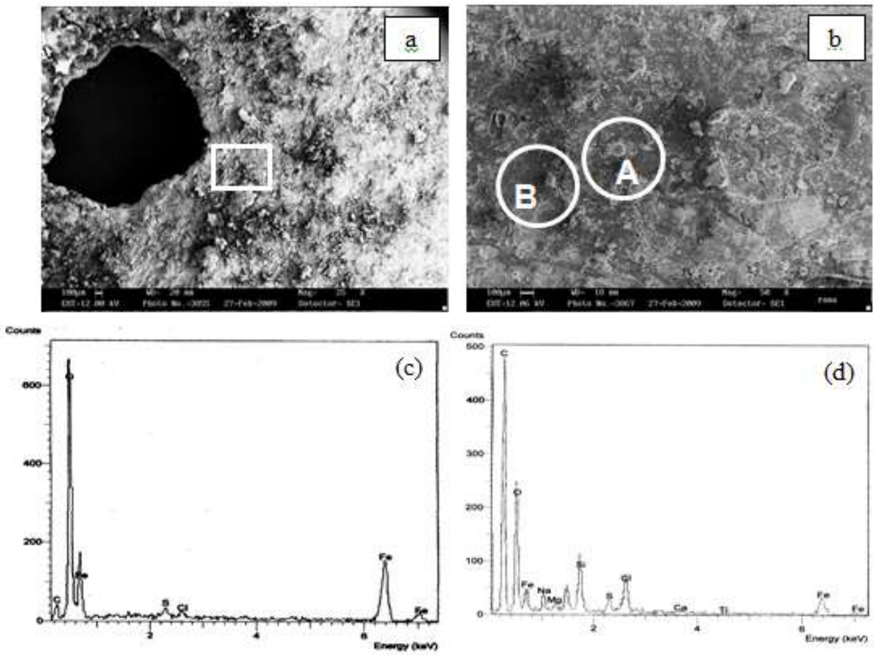

Figure 4. (a) Corrosion pits, (b) Magnified region outlined square in (a),
(c),(d) EDX spectra taken from regions marked A and B in (b) respectively

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3.7. Corrosion Rate

Corrosion rate of the steel pipeline containing water phase was measured using three-electrode cell with saturated calomel electrode (SCE) as reference electrode. Fig.5 shows polarization diagram (Tafel plot) from which the corrosion rate given as steady state current density, given in i_{corr} ($\mu A/cm^2$) can be determined. Apart from i_{corr}, corrosion rate can also be presented in the form of penetration per unit time (mpy and mm/year) as follows :

$$r = 0.129\frac{ai}{nD} = 0.129\frac{i(EW)}{D} \qquad \text{(mpy)} \qquad (1)$$

$$r = 0.00327\frac{ai}{nD} = 0.00327\frac{i(EW)}{D} \qquad \text{(mm/year)} \qquad (2)$$

where D : density (g/cm^3), i is current density ($\mu A/cm^2$) and (a/n) is equivalent weight (EW) which can be determined by :

$$EW = (N_{EQ})^{-1} \quad \text{or} \quad N_{EQ} = \Sigma\frac{f_i n_i}{a_i} \qquad (3)$$

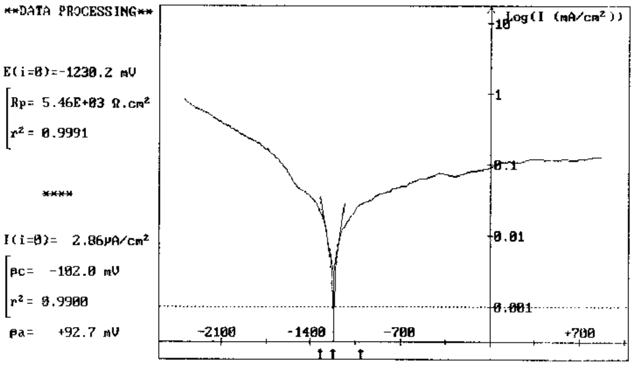

Figure 5. Tafel diagram for API 5L X46 pipeline

Using the equations above, corrosion rate for the three steel pipeline is given in Table 4. Based on grade or rank of corrosion resistance proposed by Fontana [6] as given in Table 5 the corrosion rate of the pipeline is categorized as excellent. However, corrosion specimen measured in the laboratory test was polished with no fluid flow during the test so that the measured corrosion rate would not be the same as that obtained from on-site observation but from the view point of passive-active behaviour, polarization study is useful.

Table 4. Corrosion rates of pipelines under study

Pipeline	i ($\mu A/cm^2$)	N_{EQ}	W	D (gr/cm^3)	Corrosion rate		Corrosion Resistance
					mpy	mm/year	
Gas Pipeline	2.86	0.03649	27.41	7.68	1.317	0.0334	Excellent

Table 5. Grades of corrosion rate [6]

Relative Corrosion Resistance	**Corrosion Rate**		
	mpy	**mm/year**	**µm/year**
Outstanding	< 1	< 0.02	< 25
Excellent	1 - 5	0.02 - 0.1	25 - 100
Good	5 - 20	0.1 - 0.5	100 - 500
Fair	20 - 50	0.5 - 1	500 - 1000
Poor	50 - 200	1 - 5	1000 - 5000
Unacceptable	> 200	> 5	> 5000

3.8. *Analysis of Fluid Flow*

Gas velocity (U_g) inside the pipeline under study can be determined using the following equation [7] :

$$U_g = \frac{Q_g}{A_f} \qquad (4)$$

where Q_g is gas flow rate and A_f is pipeline flow cross-sectional area. Gas flow rate is measured to be 6 mmscf/day or equivalent to 1.9664 (m^3/s) and by subsituting data into Eq.3 then the results are given in Table 6.

Table 6. Flow rate and gas velocity

Gas flow rate (Q_g) (m^3/s)	Gas velocity (U_{sg}) (m/s
1.9664	23.873

4. Discussion

Results of visual examination of API 5L X46 gas pipeline shows the presence of corrosion pits is associated with water phase present inside the gas pipeline. The occurrence of water is resulted from condensation. This argument is based on the fact that the operating pressure and temperature of natural gas are 160 psi and 90 ^oF respectively. From steam table, the dew point of water at 160 psi is around 363 ^oF (184 ^oC) which is higher than the gas temperature (90 ^oF). Therefore, it can be concluded that free condensed water may have formed as the temperature of gas falls below the water dew point. Apart from corrosion attack, the damage may come from flow effect if the gas velocity exceeds its critical value U_{crit}. The simplest and the most commonly method to avoid corrosion erosion is given in API RP-14E which gives a formula for calculating the critical flow velocity at which erosion corrosion commences [4].

$$U_{crit} = \frac{C}{\sqrt{\rho}} \qquad (5)$$

where U_{crit} is the critical velocity (ft/s), ρ is the gas/liquid mixture density (lb/ft^3) and C is constant that depends on the pipeline material.

Data on gas chromatography analysis show that the natural gas transported by the pipeline contains mainly methane (CH_4) and by taking density of methane of around 4.82 kg/m^3 (0.3009 lb/ft^3) and for steel pipeline, API RP-14E suggests a C value of 100 then the critical gas velocity is :

$$U_{crit} = \frac{C}{\sqrt{\rho}} = \frac{100}{\sqrt{0.3009}} = 182.3 \text{ ft/s} \qquad (6)$$

Or U_{crit} = 55.57 m/s

The calculated gas velocity of the pipeline is 23.87 m/s which is lower than U_{crit} and based on API RP-14E point of view this velocity is acceptable. It seems that due to low gas flow velocity, free condensed water may separate out to form a discrete phase, especially at the bottom of the gas pipeline. If this condition occurs then pitting corrosion may take place its mechanism has been proposed by Trethewey and Chamberlain [8] as shown in Fig.6

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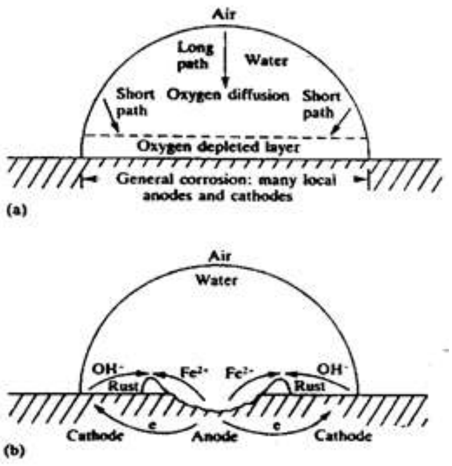

Figure 6. Mechanism of pitting corrosion [8]

As water droplets forms at the pipeline steel, air-electrolyte interface receives more oxygen compared to the area at the centre of the drop. As a result, the area at the centre of the drop acts as anode, and oxidation takes place.

$$Fe \rightarrow Fe^{2+} + 2e^{-} \qquad (7)$$

In neutral and basic condition, oxygen present in the water subsequently consumes the electrons from anode according to the following reaction.

$$H_2O + \tfrac{1}{2} O_2 + 2e^{-} \rightarrow 2OH^{-} \qquad (8)$$

The addition of the two half-reactions leads to the overall reactions as follow :

$$Fe + H_2O + \tfrac{1}{2} O_2 \rightarrow Fe(OH)_2 \qquad (9)$$

The corrosion product of ferrous hydroxide [$Fe(OH)_2$] forms a diffusion-barrier layer around the pit mouth through which oxygen must diffuse. At the outer surface of the $Fe(OH)_2$ layer, access to dissolved oxygen is easy leading to the formation of ferric hydroxide, in accord with

$$2Fe(OH)_2 + H_2O + \tfrac{1}{2} O_2 \rightarrow 2Fe(OH)_3 \qquad (10)$$

Ferric hydroxide [$Fe(OH)_3$] appears to be reddish-brown in colour. This corrosion product is periodically scoured by gas flow.

5. Conclusions

Conclusions that can be drawn from the present investigation are summarized as follows :

1. Pitting corrosion is the main cause of failure in the API 5L X46 gas pipeline. This pitting corrosion is promoted by free condensed water which separates from gas flows due to low gas velocity.
2. Pitting corrosion seems to be initiated by the damage of passive film due to chloride ions dissolved in condensed water.
3. Erosion may not significantly contribute to the damage of the gas pipeline since the gas velocity is relatively low.

6. Recommendations

Some damage prevention options for gas pipeline are proposed as follows :

1. Inspection needs to be performed to optimize the process where the more condensate out of the gas, the better the pipe condition is.
2. Optimize or properly add corrosion inhibitor dosage.
3. Prevent entrainment of sand and solids in the gas phase by using for example sand screens or gravel packs. However, sand screens increase resistance to flow entering a well and hence affect its potential productivity.
4. Keep the flow velocity high so that uniform corrosion occurs rather than pitting corrosion. However, increasing flow velocity is restricted by critical velocity recommended by API RP-14E.

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