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Dependability of Bursting Strength on Sulphate Reducing Bacteria Promoted Corrosion of Natural Gas Pipelines

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Abstract— The aim of the present work was to calculate the bursting pressure of natural gas pipelines. The external corrosion was due to sulphate reducing bacteria. The failure of the pipes was evaluated based on the Tresca, von Mises criteria, Weibull criteria and finite element analysis. The significance of crack dimensions was recognized using Taguchi techniques. The highly influencing crack dimension was crack depth. The results obtained by the modified ASME B31G have been more realistic to the actual burst of pipes.

Index Terms— Natural gas, high carbon steel, crack depth, crack length, bursting pressure, Tresca criterion, von Mises criterion.

1. Introduction

CORROSION is one of the leading causes of failures in onshore transmission pipelines. For the year 2014-15, production of natural gas is 33.656 Billion Cubic Meters (BCM) which is 4.94 % lower than production of 35.407 BCM in 2013-14 (figure 1) [1]. The corrosion was accountable for 18 percent of the significant incidents in the 20-year period from 1988 through 2008 in United States. The significant corrosion incidents were 52 per year on pipelines during the past 20 years [2].

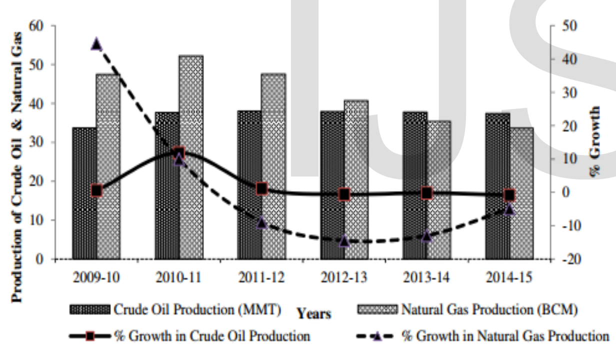

Fig. 1. Crude oil and natural gas production in India.

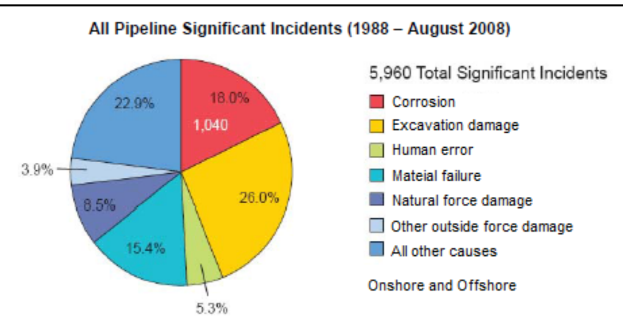

Fig. 2. Causes of significant incidents in onshore and offshore pipelines [2].

External corrosion causes more than 90 percent of corrosion-related failure in distribution pipelines. The transmission lines experiences the internal corrosion. For external corrosion, the environment could be groundwater or moist soil for onshore pipelines and seawater for offshore pipelines. For internal corrosion, the environment could be water holding sodium chloride, hydrogen sulfide and carbon dioxide. MIC (Microbiologically influenced corrosion) is caused by microbes whose actions instigate the corrosion cycle. The main types are suphate-reducing bacteria (SRB) and acid-producing bacteria (APB). Bacteria can encourage external corrosion by depolarizing the pipe through the utilization of hydrogen gas formed at the pipe surface by the cathodic protection currents [3]. Once the pipe is depolarized, corrosion can take place. The internal corrosion can happen by bacteria forming an acidic biofilm that traps electrolytes and acids. The corrosion mechanism is illustrated schematically in figure 4. The external and internal corrosions are showed in figure 5. The consequence of pipeline corrosion is the reduction of pipe strength. Even if the pressure in the gas pipeline is not increased the pipeline may burst due to deduction of pipe strength resulting property and public loss.

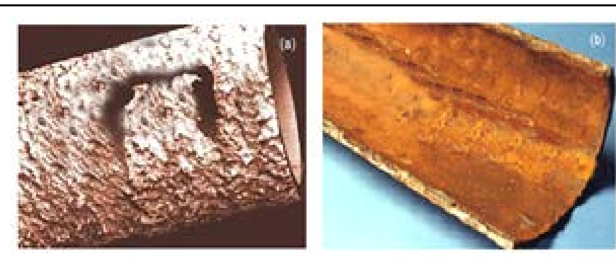

Fig. 4. Corrosion: (a) external and (b) internal

The natural gas pipeline burst at Nagaram village, Andhra Pradesh, India, Friday, June 27, 2014 is shown in figures 6 and 7. The death toll in the GAIL pipeline blast, which occurred at Nagaram village in East Godavari district of Andhra Pradesh rose to 16. The pipeline, which caught fire and exploded, claimed 15 lives on the spot. GAIL is being criticized by the villagers for "gross negligence" in maintaining the pipelines which led to the accident. In another incident flames shoot into the air after a natural gas pipeline explosion in Texas, this

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killed one man and injured seven others (figure 8).

Fig. 5. The Andhra Pradesh Chief Minister N. Chandrababu Naidu and Petroleum Minister Dharmendra Pradhan inspecting the blast site of GAIL gas pipeline blast. (AP Photo)

Fig. 7. Causalities due to GAIL gas pipeline blast.

Fig. 8. Flames shoot into the air after a natural gas pipeline explosion in Texas.

Even if research on fracture mechanics of the pipelines is well-to-do, there is no judgment method that is accurate and largely acknowledged. Most popular failure pressure methods for pressurized pipes with active corrosion defects are ASME B31G [4, 5] and modified ASME B31G [6], DNV-RP-F101 [7, 8], SHELL-92 [9, 10], RSTRENG [11, 12], PCORRC [13, 14], LG-18 [15, 16], Fitnet FSS [17, 18] and Choi criteria. Finite element methods have been applied to predict total deformation, von Misess stress, stress intensity factors and J-integral for the applied pressure on the pipes [20-22].

The present work was to predict the dependability of bursting strength on corrosion of natural gas pipelines. The corrosion was also investigated in terms of suphate-reducing bacteria (SRB) and acid-producing bacteria (APB). The bursting pressure was evaluated using ASME B31G, modified ASME B31G, DNV-RP-F101, SHELL-92, PCORRC, LG-18, RSTRENG, Fitnet FSS and Choi criteria. The Weibul criterion was applied to find the reliability of pipes. The finite element analysis was used to verify the results obtained by the computational methods.

TABLE 1

Control factors and their levels

Factor	Symbol	Level–1	Level–2	Level–3
Thickness, mm	A	3	4	5
Length of crack, mm	B	200	250	300
Depth of crack	C	40%t	50%t	60%t
Grade of high carbon steel	D	1060	1095	1080

where t is pipe thickness.

TABLE 2

Orthogonal Array (L9) and control factors

Treat No.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

2. MATERIAL AND METHODS

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The material of pipes was stainless steel. In the present study, the dimensions of the test pipe were 150 mm outer diameter and 5000 mm length. The chosen control parameters are summarized in table 1. The control factors were assigned to the various columns of orthogonal array (OA), L9 [23] is given in table 2. The dimensions of notch are given in figure 9.

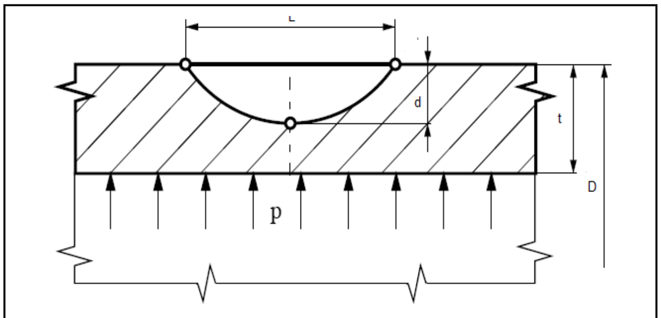

Fig. 9. The crack dimensions.

The Tresca criterion is the first classical yield criterion in the strength theory for isotropic ductile materials, often referred to as the maximum shear stress criterion. In principal stress space (σ_1, σ_2, σ_3), the Tresca criterion can be expressed as

$$\tau_{max} = \max\left(\frac{|\sigma_1-\sigma_2|}{2}, \frac{|\sigma_2-\sigma_3|}{2}, \frac{|\sigma_1-\sigma_3|}{2}\right) = \frac{\sigma_{YS}}{2} \qquad (1)$$

where τ_{max} is the maximum shear stress and σ_{uts} is the ultimate tensile strength in tension.
The von Mises criterion is the second classical yield criterion in strength theory, often referred to as the octahedral shear stress criterion. It can be expressed by the principal stresses in the form:

$$\tau_{vm} = \sqrt{\frac{1}{6}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\right]} = \frac{\sigma_{YS}}{\sqrt{3}} \qquad (2)$$

where τ_{vm} is the von Mises effective shear stress.

The von Mises yield surfaces in principal stress coordinates circumscribes a cylinder with radius $\sqrt{2/3}\,\sigma$ around the hydrostatic axis. Also shown is Tresca's hexagonal yield surface (figure 6). Intersection of the von Mises yield criterion with the σ_1, σ_2 plane, where $\sigma_3 = 0$ (figure 9).

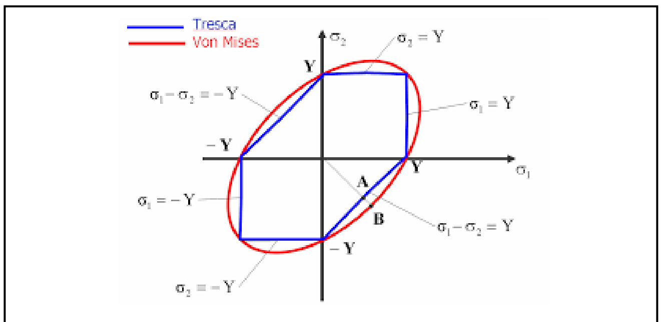

Fig. 10. Tresca and von Mises criteria.

3. Results and Discussion

The bursting pressures computed from PCORRC, ASME B31G, modified ASME B31G, DNV-RP-F101, SHELL-92, RSTRENG, Fitnet FSS and Choi criteria are given in figure 11. The lower limit represents the results obtained from ASME 31G criterion and the upper limit stands for the results obtained from RESTRENG criterion.

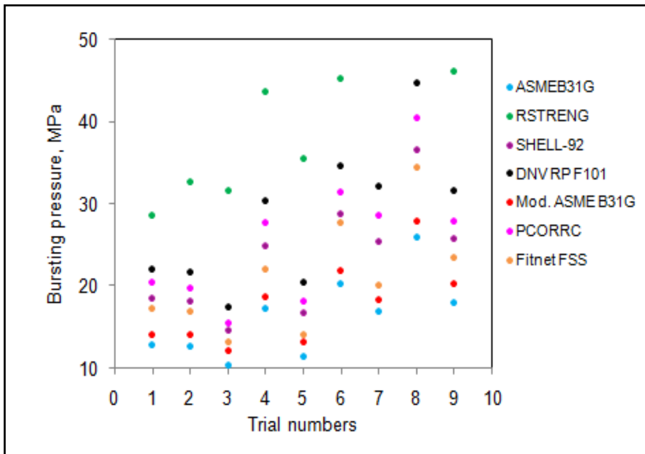

Fig. 11. Bursting pressures computed from different methods.

TABLE 3
ANOVA summary of the bursting pressure based on modified ASME 31G criterion.

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	40.33	54.00	66.53	114.5	1	114.5	24710.43	55.29
B	51.39	55.16	54.30	2.61	1	2.61	563.27	1.26
C	64.04	53.10	43.71	69.06	1	69.06	14903.95	33.35
D	47.65	988.52	160.85	20.9	1	20.9	4510.46	10.09
e				0.018535	4	0.004634	1.00	0.01
T	203.40	1150.79	325.39	207.0885	8			100

Note: SS is the sum of square, v is the degrees of freedom, V is the variance, F is the Fisher's ratio, P is the percentage of contribution and T is the sum squares due to total variation.

3.1 Influence of Crack Dimensions and Tube Material on Bursting Strength

Table 3 gives the ANOVA (analysis of variation) summary of bursting pressure. Even if all the process parameters could satisfy the Fisher's test at 90% confidence level, pipe thickness, crack depth and grade of high carbon steels had major role in the total variation of bursting pressure. The pipe thickness (A), crack depth (C) and grade of high carbon steels (D) had given, respectively, 55.29%, 33.35% and 10.09% in the total variation of the bursting pressure. The crack length (B) was insignificant.

Figure 12 shows the dependence of bursting pressure on the pie thickness. As the pipe thickness increased the pressure required to burst the pipe would also increase. If the crack depth increased, the pipe could fail even at low bursting pressure (figure 13). The required bursting pressure was high (figure 14) for the high carbon steel 1080 as compared to the other two grades (grades 1060 and 1095 high carbon steels). The yield strength, ultimate tensile strength and percentage elongation at break are, respectively, 585 MPa, 965 MPa and 17%.

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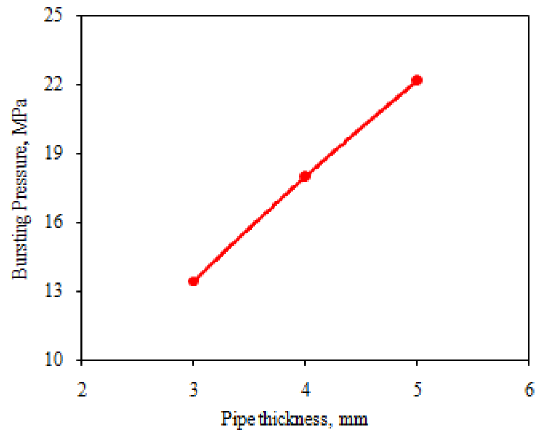

Fig. 12. Effect of pipe thickness on bursting pressure.

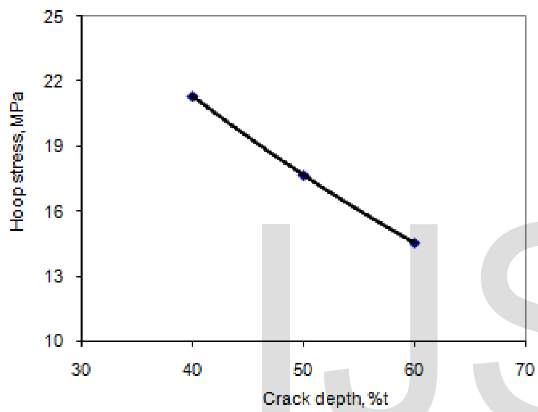

Fig. 13. Effect of crack depth on bursting pressure.

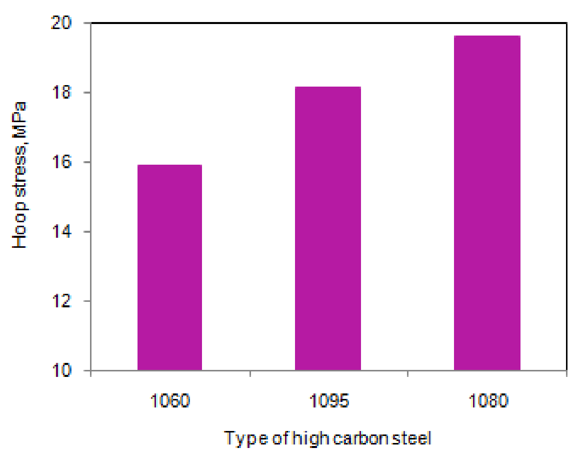

Fig. 14. Effect of high carbon steels on bursting pressure.

3.2 Failure Criteria

Table 4 and 5 give the ANOVA (analysis of variation) summary of Tresca criterion and von Mises criterion respectively. Even though all the process parameters could assure the Fisher's test at 90% confidence level, only crack depth and grade of high carbon steels had leading roles in the total variation of Tresca and von Mises criteria. The crack depth (C) contributed nearly 79.53% of the total variation in the Tresca and von Mises criteria. The grade of high carbon steel (D) put in 19.10% of the total variation in the Tresca and von Mises criteria. The pipe thickness and the crack length were insignificant in the variation of Tresca and von Mises criteria.

TABLE 4
ANOVA summary of the Tresca criterion

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	493.98	492.76	482.33	27.37	1	27.37	16579.40	0.43
B	478.72	495.06	495.29	60.18	1	60.18	36454.08	0.94
C	576.46	490.57	402.05	5069.81	1	5069.81	3071041.1	79.53
D	441.14	85466.07	1469.08	1217.33	1	1217.33	737398.55	19.1
e				0.006603	4	0.001650	1.00	0
T	1990.3	86944.46	2848.75	6374.683	8			100

TABLE 5
ANOVA summary of the von Mises criterion

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	855.61	853.49	835.42	82.1	1	82.1	33475.61	0.43
B	829.17	857.47	857.87	180.54	1	180.54	73613.71	0.94
C	998.45	849.69	696.38	15209.43	1	15209.43	6201521.1	79.53
D	764.07	256398.2	2544.51	3651.98	1	3651.98	1489065.0	19.1
e				0.009810	4	0.002452	1.00	0
T	3447.3	258958.8	4934.18	19124.04	8			100

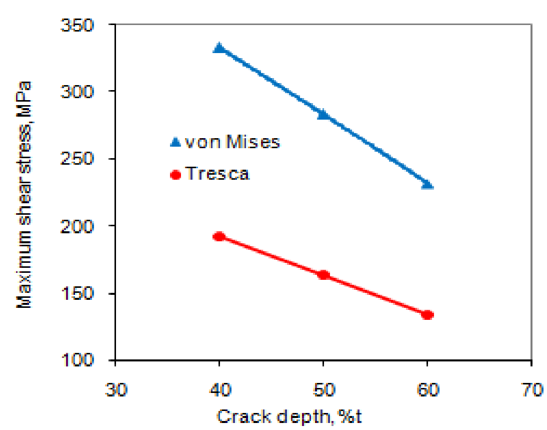

Fig. 15. Effect of crack depth on failure criteria.

As the crack depth increased the level of failure shear stress decreased (figure 15). The level of maximum shear stress was low for the 1060 high carbon steel and it was high for the 1080 high carbon steel (figure 16). As observed from figure 17a, only pipes 1 and 6 were burst under von Mises failure criterion even though all the pipes were found safe under Tresca criterion (figure 17b). With the increase of internal pressure, the stress variation through the ligament exhibits three distinct stages; elastic deformation, plastic deformation and material hardening.

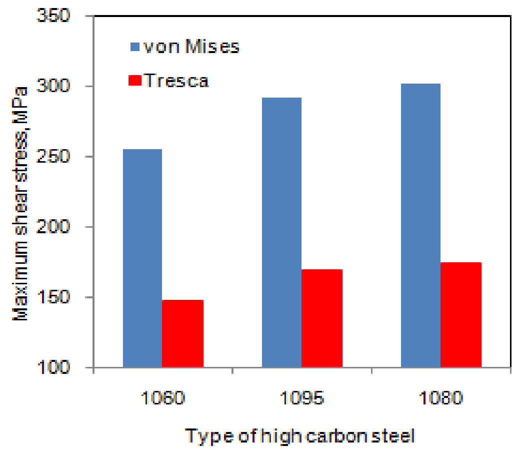

Fig. 16. Effect of high carbon steel on failure criteria

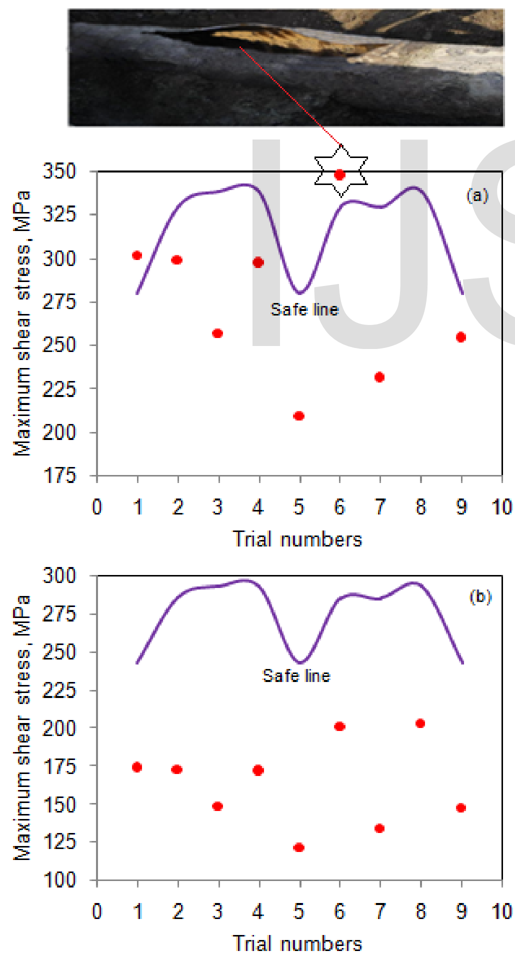

Fig. 17. Failure criterion of all pipes: (a) von Mises and (b) Tresca.

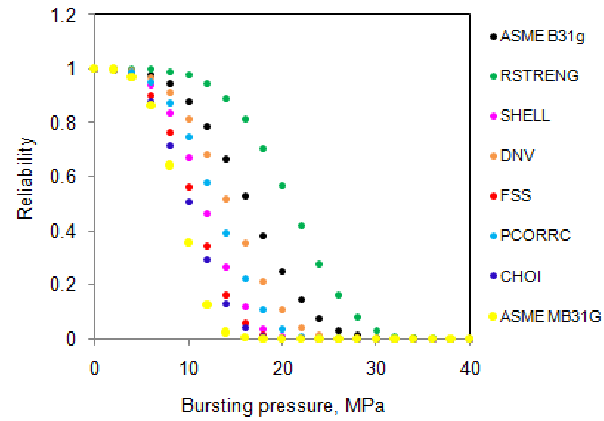

Fig. 18. Weibull failure criterion of all pipes.

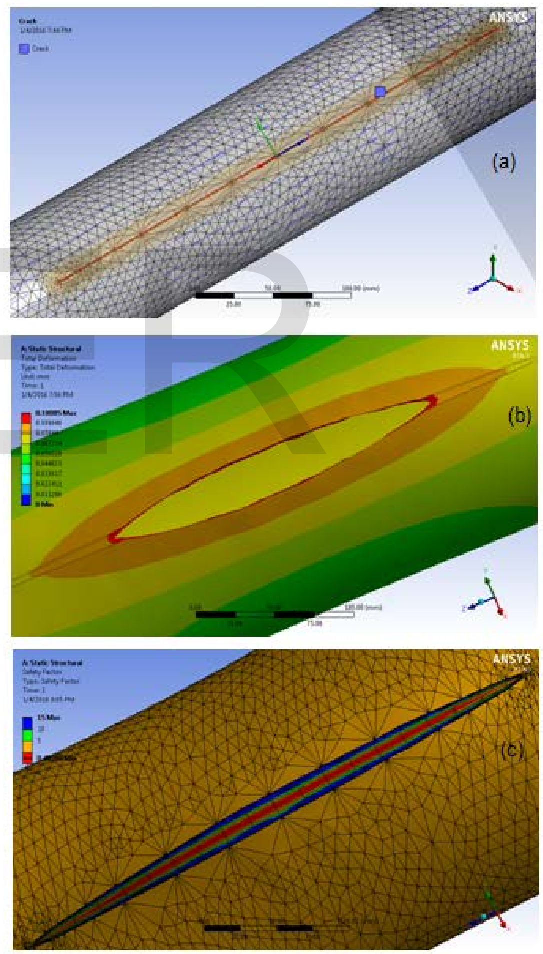

Fig. 19. Results of test condition 6 obtained by ANSYS software code.

The Weibull criterion was used to predict the reliability of all the pipes. The least reliable criterion was ASME modified 31G and the most reliable criterion was RESTRENG (figure 19). For 80% of reliability the maximum bursting pressure were, respectively, 13.34 MPa and 32.43 MPa for ASME modified 31G and RESTRENG criteria. For test condition 6 the

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bursting pressures were 21.98 MPa at danger level of reliability of 0.20. The crack dimensions of text conditions were 300mm crack length and crack depth 1.6 mm. The finite element modeling was carried out using ANSYS software code. The pipe and crack were discretized with tetrahedron elements [24] as shown in figure 19a. The crack opening (figure 19b) was matched with the experimental one (figure 17). The safety factor was about 0.4 across the crack area (figure 19c).

The reason for the failure of the pipe was due to the external corrosion (figure 20) of the pipeline attributable to (SRB) suphate-reducing bacteria. SRB can act as a catalyst in the reduction reaction of suphate to sulfide. In the presence of moisture content, the corrosion of metals begins with production of enzymes, which can accelerate the reduction of sulphate compounds to H_2S. The mechanism of SRB is as follows:

Anodic reaction: $4Fe \rightarrow 4Fe^{2+} + 8e^-$
Water dissociation: $8H_2O \rightarrow 8H^+ + 8OH^-$
Cathodic reaction: $8H^+ + 8e^- \rightarrow 8H + 4H_2$
Hydrogen oxidation: $SO_4^{2-} + 4H_2 \rightarrow H_2S + 2H_2O + 2OH^-$
Precipitation: $Fe^{2+} + H_2S \rightarrow FeS + 2H^+$
Precipitation: $3Fe^{2+} + 6OH^- \rightarrow 3Fe(OH)_2$
Total reaction: $4Fe + SO_4^{2-} + 4H_2O \rightarrow FeS + 3Fe(OH)_2 + 2OH^-$

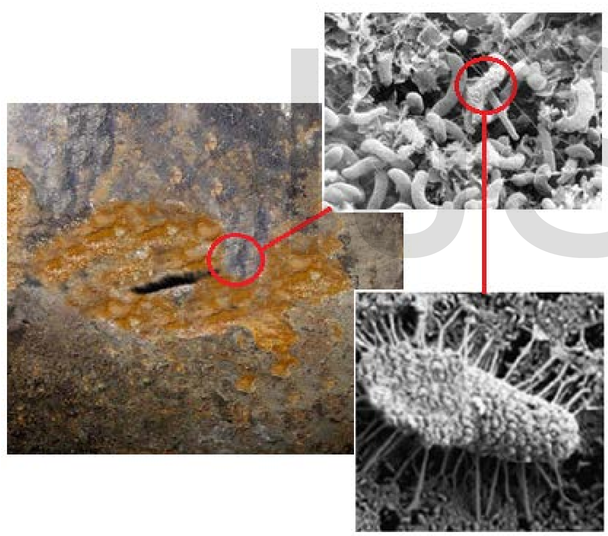

Fig. 20. External corrosion due to suphate-reducing bacteria.

The solid FeS on the metal surface played the role of absorber of molecular hydrogen. The area covered by iron sulfide becomes cathode, while biofilm area behaves as anode. The sour environments are exclusively corrosive because of high levels of hydrogen available at the metal surface or in a crack because of sulfide activation at the cathode. In the first stage, the adsorption of bacterial cells and iron sulfide products were taken place (figure 21). In the second stage, the metal was encapsulated by a combination film of iron sulfide film and extracellular polymeric substances. Bacterial corrosion and film stabilization are two major occurrences at this stage. The third stage was controlled by a local pH decrease that caused by SRB activity on the steel in the presence of HS [25].

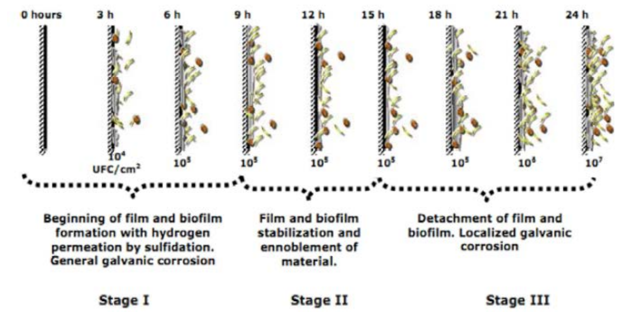

Fig. 21. Mechanism for the SRB proposed by Romero [25].

4. CONCLUSIONS

The corrosion was due to suphate-reducing bacteria. The bursting pressure is highly dependent on the crack depth and grade of high carbon steel. The bursting pressure decreases with the increase of crack depth. The von Mises criterion is very near the failure pattern of the pipes. The failure criteria would satisfy the predicted results from the finite element analysis, Weibull criterion and ASME modified 31G criterion used for the estimation of the bursting strength.

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