Sigma J Eng Nat Sci, Vol. 42, No. 2, pp. 414–424, April, 2024

Sigma Journal of Engineering and Natural Sciences
Web page info: https://sigma.yildiz.edu.tr
DOI: 10.14744/sigma.2024.00000

Research Article

Corrosion behavior of N80 tubing steel in the produced water

Duygu ARSLAN VATANSEVER[1], Simge ARKAN OZDEMIR[1,2], Nurhan CANSEVER[3], Esra ILHAN SUNGUR[4,*]

[1]*Department of Biology, Institute of Graduate Studies in Sciences, Istanbul University, Istanbul, 34134, Türkiye*
[2]*Vocational School of Health Services, Uskudar University, Uskudar, Istanbul, 34664, Türkiye*
[3]*Department of Metallurgical and Materials Engineering, Faculty of Chemistry-Metallurgy, Yıldız Technical University, Istanbul, 34220, Türkiye*
[4]*Department of Biology, Faculty of Science, Istanbul University, Istanbul, 34134, Türkiye*

ARTICLE INFO

Article history
Received: 29 April 2022
Revised: 12 July 2022
Accepted: 30 September 2022

Keywords:
Produced Water; N80 Steel; Microbiologically Induced Corrosion (MIC); Electrochemical Tests, Weight Loss

ABSTRACT

One of the most common problems encountered in the oil industry is the microbiologically induced corrosion (MIC) of steel equipment by the produced water (PW). In this aspect, PW sample, which is known to contain microorganisms, was taken from Adıyaman oil field and used in corrosion tests of N80 tubing steel. Two different laboratory scale systems, test (with non-sterile PW) and control (with sterile PW), were set up and operated at 70°C over 720 h. For corrosion analysis, the coupons were removed from the laboratory-scale systems at certain time intervals and, gravimetric and electrochemical analyses were carried out. The surface of the coupons was examined by scanning electron microscopy (SEM). The corrosion rates of the test coupons obtained from gravimetric analyses were higher than the control ones during the experiment, and the test coupons were 1.46 times more corroded at the end of the experiment. Additionally, it was determined that the current values of the test coupons were significantly higher than those in the control system ($p<0.05$). The results of corrosion analyses pointed out that N80 steel was corroded microbiologically. SEM analysis showed that microorganisms were present among the corrosion products. The corrosion data obtained from the control system also indicated that the PW was aggressive for N80 steel.

Cite this article as: Arslan Vatansever D, Arkan Ozdemir S, Cansever N, Ilhan Sungur E. Corrosion behavior of N80 tubing steel in the produced water. Sigma J Eng Nat Sci 2024;42(2):414–424.

INTRODUCTION

The produced water (PW) is a mixture of the formation water, naturally found in the oil reservoir, and injection water, injected water into the reservoir for oil recovery [1]. The chemical composition of PW is specific to the oil reservoir from which it is extracted because the different factors, such as reservoir conditions (i.e. geological formation), well structure, age of the well, and extracted product, may affect the constituents of PW. Generally, PW may

---

***Corresponding author.**
*E-mail address: esungur@istanbul.edu.tr

This paper was recommended for publication in revised form by Regional Editor Alper Uysal

Published by Yıldız Technical University Press, İstanbul, Türkiye

contain inorganic substances (e.g. calcium, sodium, chloride, potassium, sulphate, carbon dioxide, hydrogen sulphide), organic compounds, including volatile aromatic compounds (benzene, ethylbenzene, toluene, etc.), polycyclic aromatic hydrocarbons (PAHs) (e.g. naphthalene), phenol compounds, organic acids and additives, condensates, petroleum gases, sand and corrosion products [2, 3].

In oil industry, corrosion occurs with very different corrosive effects originating from PW. Electrochemical corrosion is very common due to the presence of an aqueous system in the environment [4]. Major corrosion mechanisms include sour corrosion, hydrogen crevice corrosion, microbiologically induced corrosion (MIC) etc. [5, 6]. MIC refers to metal degradation caused by corrosion reactions that occur directly with the microbial metabolic activities or indirectly with the secretion of chemically reactive products [7]. MIC is the result of a series of highly complex, interacting reactions carried out by different bacterial species [8, 9]. The ability of microorganisms to survive in oil reservoirs depends on the chemical composition and physical properties of the ecosystem. The major factors affecting the physicochemical structure of the reservoir environment are temperature, salinity, pH values and the redox potential of the environment, as well as the presence of electron donors and acceptors in the environment [10]. Microorganisms can accelerate corrosion by forming a biofilm, producing extracellular polysaccharide substances (EPS), producing deposits under which is a favorable environment for the development of crevice corrosion, creating a corrosive acidic environment with own metabolic products, breaking down the chemicals added to the environment to prevent corrosion, by directly affecting (accelerating cathodic or anodic reactions) corrosion reactions [8, 11].

Carbon steel is commonly used metal in the oil industry (storage tanks, crude pipelines, etc.), although it has low corrosion resistance [12]. The reason for this may be due to its highly developed technology and advantages in terms of cost-effectiveness [13]. The carbon steels such as N80, P110, Q235 etc. are generally preferred in studies conducted to investigate the corrosion of carbon steel used in the oil industry [13-15].

The oil content in different countries in the world differs in terms of both chemical and microorganism diversity and density. Therefore, every oil field is special in itself and microorganism-based corrosion problems should be handled as specific to the oil fields where the trouble arised. Adıyaman region is one of the important oil production regions of Türkiye and known to have intense corrosion problems. In addition, as revealed in our previous study [16], the oil PW taken from this region is rich in mixed bacterial population. In this context, it was aimed to reveal whether the microorganisms in the PW have a role in the corrosion of N80 steel, which is frequently used material both in the region and in general oil production activities, in the present study. For this purpose, N80 steel was exposed to PW taken from Adıyaman oil field over 720 h. The corrosion behavior of N80 steel was investigated by performing electrochemical and gravimetric analyses at certain sampling times. Scanning electron microscopy (SEM) analysis was applied to examine the coupon surfaces.

MATERIALS AND METHODS

PW Sampling and Analyses

PW was used as working solution in the experiments. The PW sample known to be rich in bacterial content was taken from Adıyaman oil field located in the Southeastern Anatolia Region of Türkiye [16]. The sample was collected under aseptic conditions in sterile 500 mL serum bottles and the bottles were immediately capped to prevent oxygen inlet. Temperature and conductivity data of the PW were obtained from Türkiye Petrolleri Anonim Ortaklığı (TPAO), and some physicochemical parameters (alkaline, conductivity, total chlorine, dissolved oxygen, etc.) were analysed by AEM Environmental Laboratory.

Test Material

N80 steel, which is frequently used as tubing material, was used as test material [14]. N80 steel was supplied by Adıyaman Regional Directorate of TPAO as an unused tubing pipe prepared according to the American Petroleum Institute (API) standards. The N80 steel consists of the following chemical composition (wt.%): Fe 97.60, Mn 1.18, Ni 0.56, Si 0.285, C 0.24, Cr 0.104, P 0.0189, S 0.0157, Mo 0.015, Cu 0.012. The coupons (6×5×21 mm) were cutted from the tubing pipe (Figure 1) and then were drilled from one edge to form a 2.5 mm diameter hole. After all the coupon surfaces were polished with emery papers (180, 240, 320, 400, 600, 800 grit), the coupons were washed, dried and stored in a desiccator until use.

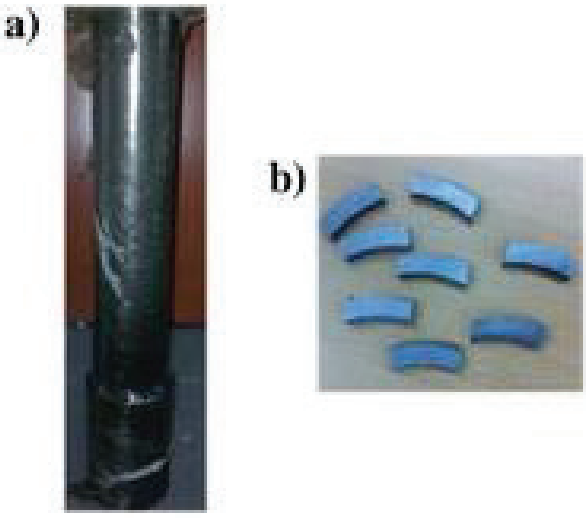

Figure 1. The tubing pipe (a) and the coupons obtained from the tubing pipe (b).

The corrosion behavior of N80 steel was detected by both gravimetric and electrochemical methods. Therefore, the coupons were prepared separately as required by these analyses. The coupons to be used in gravimetric analysis were weighed. For electrochemical analysis, the coupons were coated with an epoxy zinc phosphate primer (Moravia, Türkiye) and then with an epoxy final coating (Moravia, Türkiye) to leave an area of 1 cm^2 on a surface in contact with the PW sample. Afterwads, the epoxy coated areas on the surfaces were finally covered with silicone. All the coupons were sterilized by UV (UVC, 254 nm, 15 W) for 15 min.

Installation and Operation of Experimental Systems

In order to perform the corrosion experiments, a test system on a laboratory scale was set up, which included a sterile 1 L glass beaker, a grid as coupon bearer, and N80 steel coupons. The PW sample was used as the working solution. The coupons attached to the carrier grid were located into the glass beaker under aseptic conditions. The system was operated uninterruptedly at 70°C over 720 h. A magnetic stirrer (IKA C-MAG HS 10) set at 150 rpm was used to mix the working solution during the process. As soon as the coupons were exposed to the PW sample, the experiment began (0 h of exposure). From the moment that the coupons were exposed to the PW sample, the experimental period began to run. A control system was simultaneously installed and operated under the same conditions with the test system. Sterile PW sample (without microorganism) was used as the working solution in the control system. Sterility control was carried out in terms of anaerobic and aerobic bacteria by inoculating of the sterile PW onto R2A agar and sodium thioglycolate agar, respectively, at each measurement time.

Corrosion analyses were performed with the coupons taken from the test and control systems at certain sampling times (24, 48, 72, 96, 144, 168, 336 and 720 h) by both gravimetric and electrochemical methods. Additionally, electrochemical measurements were applied also at 504th h of exposure. SEM analysis was carried out to observe the surface of the coupons.

Gravimetric Analysis

For the weight loss measurement, three coupons were taken from both of the systems. Clarke's solution was used to remove corrosion products from the coupons' surfaces [17]. Then they were dried in the Pasteur oven. After the weight loss of the coupons were determined, the corrosion rates were calculated with the formula given in the equation below [17].

Corrosion rate (V_{corr}) was calculated in mpy (miles/year) and represented 1 mile thinning in one year (1 mile = 0.0254 mm)

V_{corr} (mpy): $(K \times W) / (A \times t \times d)$
K: 3.45×10^6 (constant for mpy)
d: density of coupon (g/cm^3)
W: weight loss (g)
A: surface area (cm^2)
t: experimental time of (h)

Electrochemical Analysis

Electrochemical measurements were performed in a conventional three-electrode corrosion cell by means of a potentiostat/galvanostat device (Gamry, Interface 1000, USA). The N80 steel coupons was used as the working electrode, while the counter electrode was carbon rods and a saturated calomel electrode (SCE) was used as the reference. After open circuit potential (OCP) values of the coupons were measured, potentiodynamic curves were obtained. The potentiodynamic polarization scans were conducted from -1.000 V to -0.400 V at a scanning rate of 1mV/s. After potentiodynamic polarization tests, corrosion potential (E_{corr}) and corrosion current (i_{corr}) were determined. Electrochemical measurements were carried out at certain times (24, 48, 72, 96, 144, 168, 336, 504 and 720 h). For each measurement, a coupon was removed from the test and control systems.

SEM Analysis

The surfaces of the coupons were analysed by SEM. The coupons were fixed with 2.5% glutaraldehyde, then gradually dehydrated in ethanol series (30%, 50%, 80%, and 95%) for 10 min and finally dried in air [18]. Images were taken by a scanning electron microscope (FEI Quanta 450 FEG, magnification range: from 6 × to 10^6 ×) after the dried samples were coated with gold.

Statistical Analysis

SPSS Statistics Version 24.0 software was used for the statistical analyses. The relationship between the test and control data obtained by gravimetric and electrochemical methods was determined by the Pearson and Spearman correlation coefficients test. Also, the numerical status and comparison of the test and control data obtained by gravimetric and electrochemical methods in terms of means were determined with the t-test and Mann Whitney U test. Except where otherwise stated, p values of 0.05 were used to determine statistical significance for all analyses.

RESULTS AND DISCUSSION

Produced Water

The results of the physicochemical analysis of the PW sample are presented in Table 1. The temperature of the PW was 70°C and therefore the systems were operated at this temperature. Although Mn and Cl contents were found to be lower, the other analysed parameters were typical for PW.

It has been reported that while the PWs contain SO_4^{-2} up to several thousand mg/L, the dissolved oxygen amount is generally low, the Fe content varies from trace amounts

Table 1. Some physicochemical parameters of the PW

Parameter	Unit	Result
Total Alkalinity	mg/L	416.8
HCO_3^-	mg/L	416.8
Dissolved Oxygen	mg/L	8.14
Fe^{+2}	mg/L	0.091
PO_4^{-3}	mg/L	<1
H_2S	mg/L	<0.1
Conductivity	ms/cm	30.2
Mn^{+2}	µg/L	56.8
NO_3^-	mg/L	<1
NO_2^-	mg/L	<0.05
CO_2	mg/L	<10
SO_4^{-2}	mg/L	673.52
Total Dissolved Solids (TDS)	mg/L	18256
Total Fe	mg/L	2.35
Total Cl	mg/L	0.63

to 1 mg/L, the PO_4^{-3} content is generally less than 1 mg/L. Also, the Mn content has been reported to range from 1 to 6 mg/, the Cl content has been usually at high (200000 mg/L or more) concentrations, and the NH_4 content can be variable [19].

Despite harsh conditions in oil reservoirs (e.g. low oxygen, high salinity, high temperature,), many microorganisms with different metabolic capabilities are able to survive in the oil reservoir environment [20]. The identified microbial groups in oil fields are sulfate reducing bacteria (SRB) [21], sulfur oxidising bacteria [22], methanogens [23], fermentative microorganisms [24], acetogens [25], nitrate reducers [26], manganese reducers [27], iron reducers [28], and hydrocarbon degraders [29]. Although the microbial community composition may differ significantly in reservoirs located in remote geographical areas, it is likely that microbial groups with similar metabolic activity can be seen in the reservoirs, located in the same region, due to having similar physicochemical reservoir conditions. For instance, nitrate-reducing and hydrocarbon-degrading *Pseudomonas stutzeri,* was reported to be abundant in oil-associated environments (e.g. PW) of south-eastern Türkiye, including Adıyaman [30], Diyarbakır [31] and Batman regions [32]. Apart from nitrate-reducers and hydrocarbon-degraders, fermentative bacteria (e.g. *Thermovirga*, *Petrotoga*), acetogens (e.g. *Acetobacterium*, *Proteiniphilum*) and sulfate reducers (e.g. *Desulfosporosinus*, *Desulfovibrio*, *Thermodesulfovibrio*, *Desulfotomaculum*) were also detected in the Diyarbakır oil fields located in southeastern Türkiye [33]. In addition, not only Diyarbakır but also Adıyaman oil fields harbor fermentative bacteria (e.g. *Thermovirga*, *Geotoga*, *Sphaerochaeta*) and SRB (e.g. *Desulfovibrio*, *Paucidesulfovibrio, Oleidesulfovibrio*) [16].

The viability and metabolic activity of oil microorganisms is dependent on the availability of the mineral nutrients in the PW. Different types of microorganisms require different mineral nutrients such as macronutrients including carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), sulphur (S), chlorine (Cl), iron (Fe) elements, and micronutrients including manganese (Mn) for growth. The microorganisms derive these elements in different chemical forms found in PW. For example, SRB derive S from SO_4^{-2} or nitrate-reducing bacteria derive N from NO_3^- [34]. Especially, the high SO_4^{-2} content (673.52 mg/L) detected in the PW in the present study may point out the high probability presence of the SRB in the reservoir.

Corrosion Analyses

At the end of the analyses, a thick black layer was observed on the surface of the test coupon, while it was observed that this layer was red in the control coupons (Figure 2). SEM images revealed that the corrosion products accumulated on the test coupons were in a sandy structure and in layers on top of each other (Figure 3).

It was observed that the corrosion products accumulated on the surface of both test and control coupons in a short time, and these products completely covered the surface and thickened over time (Figure 2). Formation of thicker corrosion product on the surface of the coupons with the increased immersion time may be an indication of that the layer formed was not protective and therefore the corrosion process of N80 steel continued. Wang et al. [35] investigated the effect of PW at different temperatures on corrosion and found out that the corrosion rate increased proportionally at temperatures up to 70°C, but not proportionally when the temperature reached 80°C -90°C. They suggested that a protective corrosion product layer forms on the surface of the metal at temperatures above 70°C.

After the removal of the corrosion products, numerous pits were observed on the test coupon surface (Figure 4a).

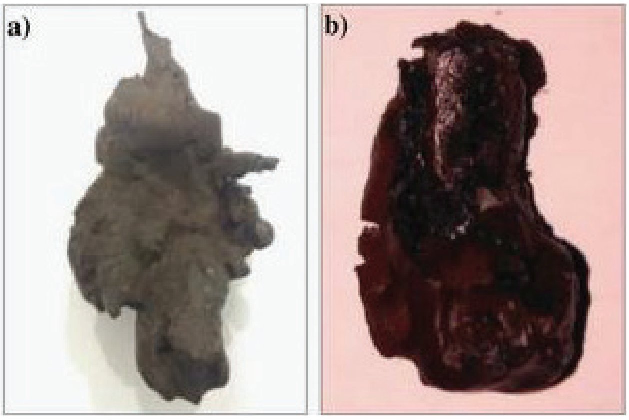

Figure 2. Macroscopic views of the corrosion products formed on the test (a) and control (b) coupons exposed to the PW.

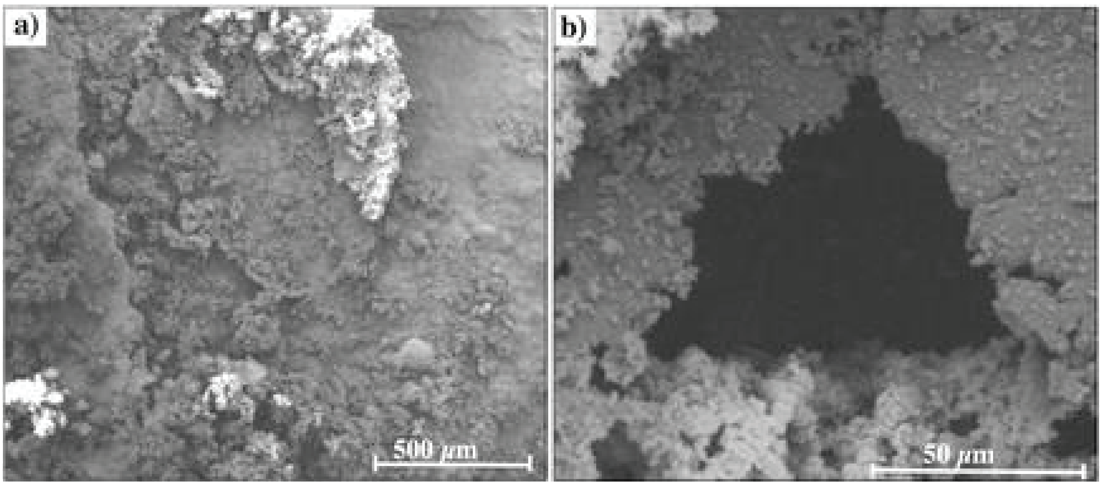

Figure 3. SEM micrographs of the corrosion products formed on the test coupon. a) Bar=500 µm, b) Bar=50µm.

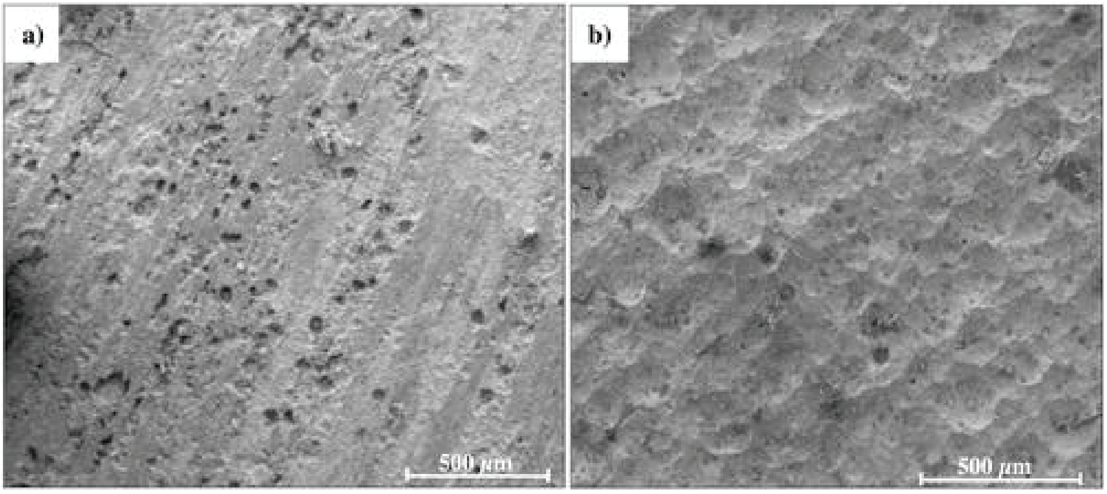

Figure 4. SEM micrographs of the test (a) and control (b) coupons after removal of corrosion products (Bars=500 µm).

However, pits were also observed on the control coupon surface, albeit less in number than on the test ones (Figure 4b). It was also detected that the surface topography of the control coupon was different from that of the test coupon. The pits formed on the surface of the control coupons may be due to the physicochemical content of the PW (Table 1). It was reported that the intense salt content causes pits on steel surfaces [36, 37]. Liu et al. [3] notified that CO_2 causes corrosion of N80 steel. Perez [38] also reported that CO_2, temperature, pH, H_2S, O_2 and organic acids cause corrosion in the oil industry, either being alone or in their interactions. In addition, Craig [39] notified that the water amount in the oil content increases the corrosive potential of the solution due to the conductivity. Moreover, Gonzalez-Rodriguez et al. [40] reported that, the passive film on the surface of the metal deteriorates and anodic dissolution begins in the presence of high amounts of $HCO_{3.}$

Gravimetric Analysis

The results of the weight loss and corrosion rate of the coupons are given in Table 2. It was determined that the weight loss values both of the test and control coupons increased with time ($p<0.01$ and $p<0.01$, respectively), and the highest values were detected as 0.1598 ± 0.0038 g/cm^2 and 0.1030 ± 0.0040 g/cm^2 at the end of the experiment, respectively. The highest corrosion rate in the test coupons was determined as 25.55 ± 2.10 mpy after 24 h of exposure, and then decreases and increases in the values were determined during the experiment. The corrosion rate of the test coupons at the end of the experiment was determined as 19.07 ± 1.82 mpy. In the control coupons, the corrosion rate varied during the experiment and the highest value was

Table 2. The weight losses and corrosion rates of the N80 steel coupons over the experiment

Time (h)	Weight loss, g/cm^2		Corrosion rate, mpy		
	Test system	Control system	Test system	Control system	Test / Control
24	0.0070 ± 0.0002	0.0031 ± 0.0001	25.55 ± 2.10	10.97 ± 0.98	2.33
48	0.0083 ± 0.0004	0.0057 ± 0.0002	15.81 ± 1.15	10.46 ± 1.01	1.51
72	0.0104 ± 0.0010	0.0073 ± 0.0002	13.30 ± 1.89	9.30 ± 1.21	1.43
96	0.0185 ± 0.0012	0.0173 ± 0.0011	17.75 ± 2.13	16.52 ± 1.30	1.07
144	0.0295 ± 0.0005	0.0248 ± 0.0010	18.21 ± 1.92	15.27 ± 1.93	1.19
168	0.0298 ± 0.0011	0.0274 ± 0.0021	15.75 ± 1.75	14.49 ± 2.01	1.09
336	0.0617 ± 0.0021	0.0546 ± 0.0019	16.75 ± 1.16	15.17 ± 1.80	1.10
720	0.1598 ± 0.0038	0.1030 ± 0.0040	19.07 ± 1.82	13.07 ± 1.72	1.46

± Standard deviation.

measured as 16.52 ± 1.30 mpy after 96 h of exposure. The corrosion rate of the control coupons was determined as 13.07 ± 1.72 mpy at the end of the experiment. It was determined that the corrosion rates of the test coupons were higher than those of the control until the end of the experiment, and the test coupons were corroded 1.46 times more than the control coupons after 720 h of exposure (Table 2). This result may indicate that microorganisms are responsible for the corrosion of the N80 steel.

Electrochemical Analysis

Although the electrochemical measurements were made over the 720 h-period of exposure, accurate data could be obtained at the last after 504 h of exposure because of the intense corrosion products on the coupon surfaces. The potentiodynamic polarization curves are shown in Figure 5. E_{corr} values of the coupons in the both systems varied during the experiment (Table 3). On the other hand, when compared with the control coupons, the E_{corr} values of the

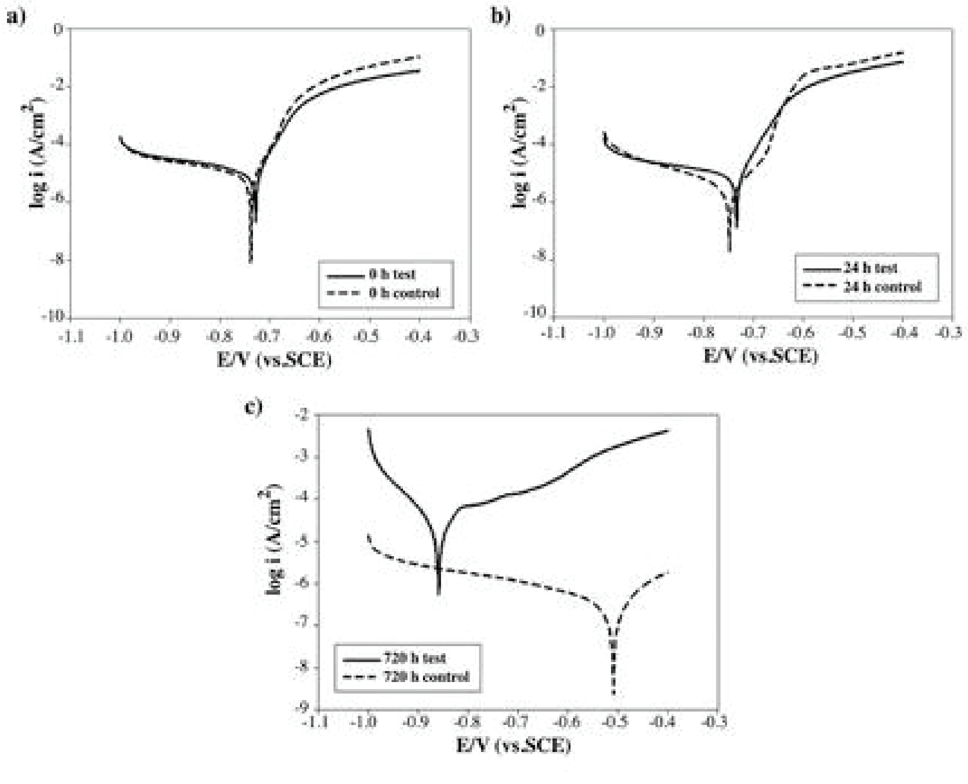

Figure 5. The potentiodynamic polarization curves of the test and control coupons exposed to the PW. a) 0 h, b) 24 h, c) 504 h.

Table 3. Electrochemical parameters of the N80 steel coupons in the test and control systems over 720 h

Time (h)	*E*corr (V)		*i*corr (μA/cm^2)	
	test	**control**	**test**	**control**
0	-0.729	-0.739	12.33	4.06
24	-0.734	-0.748	8.97	3.38
48	-0.749	-0.795	8.53	3.26
72	-0.762	-0.817	7.00	6.52
96	-0.796	-0.750	5.38	2.84
144	-0.795	-0.826	9.20	2.24
168	-0.805	-0.830	13.11	4.35
336	-0.811	-0.796	42.20	30.77
720	-0.859	-0.509	17.15	0.17

test coupons generally shifted to more positive values was determined. The most negative value of the test coupon was determined as -0.888 V after 504 h of exposure (Table 3, Figure 5c). Additionally, the current density (i_{corr}) values of the test coupons decreased until 96 h of exposure and then started to increase until the end of the experiment and was determined after 504 h of exposure as 151.30 μA/cm^2. The polarization curve belong to 504 h of exposure may indicate that cathodic reaction increased and cathodic depolarization produced on N80 steel in the presence of consortium. Indeed, similar findings for MIC of N80 steel by SRB were reported by Song et al. [41]. On the other hand, i_{corr} values of the control coupons varied during the experiment and was determined after 504 h of exposure as 29.84 μA/cm^2. It was detected that the i_{corr} values of the test coupons were

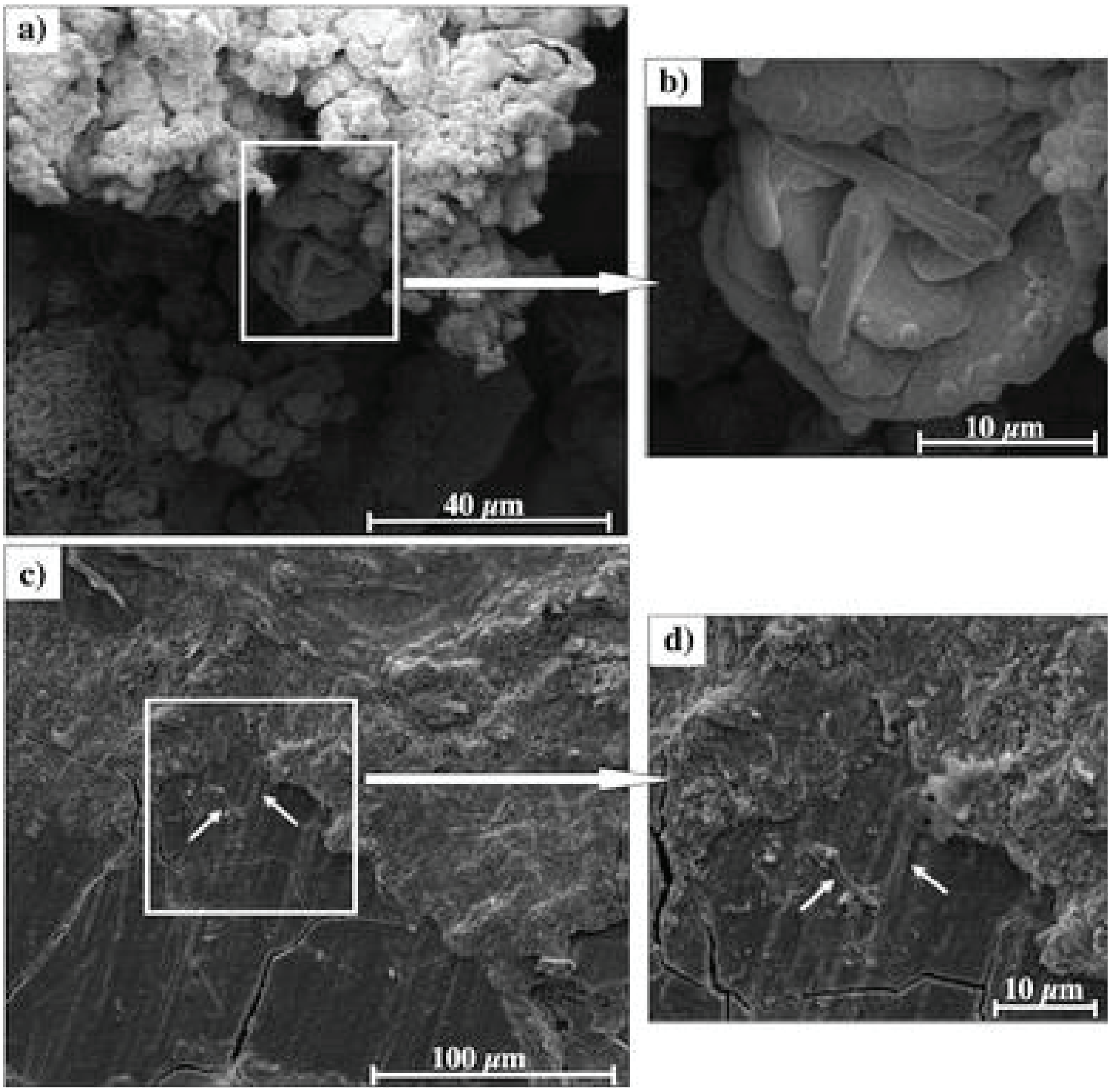

Figure 6. SEM micrographs of the microorganisms in the corrosion products on the surface of coupons in the test system (Arrows indicate microorganisms). a) Bar=40μm, b) Bar=10μm, c) Bar=100 μm, d) Bar=10 μm.

significantly higher than the control ones during the experiment ($p<0.05$).

The findings obtained from the electrochemical and gravimetric experiments could be interpreted as microorganisms encouraged the corrosion of N80 steel. It may be caused by the metabolic processes of microorganisms. Indeed, SEM images shows the presence of microorganisms on the coupon surface (Figure 6). Nevertheless, it was not clearly investigated which groups of microorganisms affect the corrosion behavior of N80 steel, nor how they were involved in the process. To the knowledge of the authors, although the corrosive effect of the mixed consortium of microorganisms in PW was investigated in different carbon steels such as API 5L [42, 43], L245 [44], and L360 [45], no similar study has been found showing the effect on the corrosion of N80 steel. However, Song et al. [41] investigated corosion behavior of N80 steel exposed to pure SRB strains isolated from oilfield PW using gravimetric and electrochemical methods during 5 and 3 days, respectively. In line with the findings obtained from both analyses, they stated that SRB corroded the N80 steel. The corrosion rate according to the weight loss was 0.0093 mm/y in the presence of SRB. It was noticed that the reported data were even lower than the values obtained after 96 h of exposure (day 4) in the present study. This may because the diverse mixed microbial community in the present study exhibited different corrosion mechanisms. Indeed mixed-culture microorganisms can form synergistic biofilms that are more tenacious when compared with the biofilms of single-strain microorganism [46].

In order to propound the corrosion mechanisms for N80 steel exposed to PW with mixed consortium, it is primarily necessary to determine corrosion-related microorganism groups that are actively present on the metal surface and even in the corrosion products. The microbial groups leading to MIC in oil associated environments mainly include SRB, sulfur-oxidizing bacteria (SOB), iron-reducing bacteria (IRB), iron-oxidizing bacteria (IOB), acid-producing bacteria (APB), nitrate-reducing bacteria (NRB), and slime-forming bacteria (SFB) [47]. Anaerobic SRB considered as the main culprits of corrosion failures of carbon steel structures due to anoxic reservoir conditions. SRB utilize sulfur compounds, such as sulfate (SO_2^{-4}), thiosulfate ($S_2O_3^{2-}$), and sulfite (SO_3^{2-}) and, as well as sulfur (S^0) to sulfide (H_2S) [48]. In the oil field steel pipe, high SO_2^{-4} concentrations of PW can facilitate SRB growth, causing not only faster corrosion of the steel, but also blocking the reservoir due to H_2S and FeS produced by SRB [47]. Extensive researches revealed that numerous factors are associated with SRB-induced MIC, including bacterial metabolic activity as well as various corrosion mechanisms such as cathodic depolarization [49], iron sulfide precipitation [50], a volatile phosphorus compound [51], Fe-binding exopolymers [52], electron-MIC (EMIC) and chemical-MIC (CMIC) [53], and the extracellular electron transfer-MIC (EET-MIC) [54, 55].

Within this scope, bacteria associated with biocorrosion were reported in the PW taken from the reservoir in Adıyaman oil field with corrosion problem in wellhead equipments [56]. In the reported study, SO_4^{-2} amount in the PW was measured as 170 mg/L, and SRB species, including *Desulfovibrio* genus (e.g., *D. dechloracetivorans) and Desulfovibrio*-like bacteria (e.g., *Paucidesulfovibrio capillatus*, *Paucidesulfovibrio longus*, and *Oleidesulfovibrio alaskensis*) were detected in the enrichments obtained from the PW. In addition, besides SRB, H_2S generating bacteria, such as *Geotoga* and *Thermovirga*, were also detected in these enrichments. Members of *Geotoga* and *Thermovirga* genera, known as fermenters, may contribute to MIC by reducing elemental sulfur with the hydrogen they produce to H_2S, a corrosive product [57, 58]. Considering the present study, it can be interpreted that the relatively higher amount of SO_4^{-2} detected in the PW (673.52 mg/L) may stimulate SRB growth in the PW and thus encourage SRB to have a significant impact on the corrosion of N80 steel.

CONCLUSION

While this study reveals the scientific importance of the studies carried out with a mixed microbial consortium in its natural environment, it will also serve as a reference for future studies on MIC control in oil environment.

Based on the obtained data, the conclusions can be drawn as follows:

- According to the electrochemical and gravimetric corrosion test results, the N80 steel was microbiologically corroded.
- The formation of thick corrosion layers on the surfaces of both test and control coupons together with the occuring of pits on the control coupons indicated that the PW was aggressive for the N80 steel.
- In line with the corrosion data obtained, the question of whether the use of N80 steel as tubing steel is economical and long-lasting comes to the fore. Therefore, more experimental studies are needed to clarify this interpretation.

ACKNOWLEDGEMENTS

The authors acknowledge the Turkish Petroleum Corporation for permission for sampling, and Bedih GÜMÜŞ and Zekeriye KILIÇKARA for their assistance during the sampling process. As well, the authors would like to thank Tuğçe TÜCCAR for her assistance.

FUNDING

This study was funded by Scientific Research Projects Coordination Unit of Istanbul University. Project number: FYL-2018-28699.

DATA AVAILABILITY STATEMENT

It is confirmed by the authors that the data supporting the findings of the study are available in the article. In accordance with reasonable requests, the raw data supporting the findings of this study are available from the corresponding author.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare in regard to the research, authorship, and/or publication of this article.

ETHICS

The publication of this manuscript has no ethical problems exist.

REFERENCES

[1] Ekins P, Vanner R, Firebrace J. Zero emissions of oil in water from offshore oil and gas installations: Economic and environmental implications. J Clean Prod 2007;15:1302–1315. [CrossRef]

[2] Lopez DA, Perez T, Simison SN. The influence of microstructure and chemical composition of carbon and low alloy steels in CO_2 corrosion. A state-of-the-art appraisal. Mater Des 2003;24:561–575. [CrossRef]

[3] Liu X, Okafor PC, Zheng YG. The inhibition of CO_2 corrosion of N80 mild steel in single liquid phase flow by aminoethyl imidazoline derivatives. Corros Sci 2009;51:744–751. [CrossRef]

[4] Corbin D, Willson E. New technology for real-time corrosion detection, In: Tri-Service Corrosion Conference; 2007 Jan; USA. 2007. pp. 1-14.

[5] Oxford W, Foss R. Corrosion of oil and gas well equipment. Nelson, Canada: Harropian Books; 1958.

[6] Brondel D, Edwards R, Hayman A, Hill D, Mehta S, Semerad T. Corrosion in the oil industry. Oilfield Rev 1994;6:4–18.

[7] Hadley R.F. Corrosion by micro-organisms in aqueous and soil environments. In: Uhlig HH editor. Corrosion handbook; 1948; USA: John Wiley & Sons; 1948.

[8] Videla HA. Microbially induced corrosion: An updated overview. Int Biodeterior Biodegr 2001;48:176–201. [CrossRef]

[9] Beech IB, Sunner J. Biocorrosion: Towards understanding interactions between biofilms and metals. Curr Opin Biotechnol 2004;15:181–186. [CrossRef]

[10] Magot M, Ollivier B, Patel BKC. Microbiology of petroleum reservoirs. Anton Leeuw 2000;77:103–116. [CrossRef]

[11] Videla HA, Herrera LK. Microbiologically influenced corrosion: ooking to the future. Int Microbiol 2005;8:169–180.

[12] Popoola LT, Grema AS, Latinwo GK, Gutti B, Balogun AS. Corrosion problems during oil and gas production and its mitigation. Int J Ind Chem 2013;4:1–15. [CrossRef]

[13] Okafor PC, Liu CB, Zhu YJ, Zheng YG. Corrosion and corrosion inhibition behavior of N80 and P110 carbon steels in CO_2-saturated simulated formation water by rosin amide ımidazoline. Ind Eng Chem Res 2011;50:7273–7281. [CrossRef]

[14] Zhu SD, Fu AQ, Miao J, Yin ZF, Zhou GS, Wei JF. Corrosion of N80 carbon steel in oil field formation water containing CO_2 in the absence and presence of acetic acid. Corros Sci 2011;53:3156–165. [CrossRef]

[15] Liu H, Fu C, Gu T, Zhang G, Lv Y, Wang H, et al. Corrosion behavior of carbon steel in the presence of sulfate reducing bacteria and iron oxidizing bacteria cultured in oilfield produced water. Corros Sci 2015;100:484–495. [CrossRef]

[16] Tüccar T, Sungur E. Potential syntrophic halophilic partners in sulfate-reducing bacterial enrichments obtained from an oil field, In: World Microbe Forum (Online Worldwide, An ASM & FEMS collaboration); 2021 Jun.

[17] ASTM-American Society for Testing And Material. Standard practice for preparing, Cleaning, and Evaluating Corrosion Test Specimens [standard G1-03], In: ASTM Int. ASTM Handbook 3.02 Corrosion of Metals, Wear and Erosion, West Conshohocken, PA, 2017.

[18] Campanac C, Pineau L, Payard A, Baziard-Mouysset G, Roques C. Interactions between biocide cationic agents and bacterial biofilms. Antimicrob Agents Chemother 2002; 46;1469–1474. [CrossRef]

[19] Collins AG. Geochemistry Of Oilfield Waters. Amsterdam, Netherlands: Elsevier; 1975.

[20] Varjani SJ, Gnansounou E. Microbial dynamics in petroleum oilfields and their relationship with physiological properties of petroleum oil reservoirs. Bioresour Technol 2017;245:1258–1265. [CrossRef]

[21] Hussain A, Hasan A, Javid A, Qazi JI. Exploited application of sulfate-reducing bacteria for concomitant treatment of metallic and non-metallic wastes: A mini review. 3 Biotech 2016;6:1–10. [CrossRef]

[22] Tian H, Gao P, Chen Z, Li Y, Li Y, Wang Y, et al. Compositions and abundances of sulfate-reducing and sulfur-oxidizing microorganisms inwater-flooded petroleum reservoirs with different temperatures in China. Front Microbiol 2017;8:143. [CrossRef]

[23] Berdugo-Clavijo C, Gieg LM. Conversion of crude oil to methane by a microbial consortium enriched from oil reservoir production waters. Front Microbiol 2014;5:197. [CrossRef]

[24] Bidzhieva SK, Sokolova DS, Tourova TP, Nazina, TN. Bacteria of the genus *sphaerochaeta* from low-temperature heavy oil reservoirs (Russia). Microbiol 2018;87: 757–765. [CrossRef]

[25] Liu JF, Sun XB, Yang GC, Mbadinga SM, Gu JD, Mu BZ. Analysis of microbial communities in the oil reservoir subjected to CO2-flooding by using functional genes as molecular biomarkers for microbial CO2 sequestration. Front Microbiol 2015;6:236. [CrossRef]

[26] Okoro CC, Amund OO. Microbial community structure of a lowsulfate oil producing facility indicate dominance of oil degrading/nitrate reducing bacteria and methanogens. Pet Sci Technol 2018;36:293–301. [CrossRef]

[27] Greene AC, Patel BK, Sheehy AJ. Deferribacter thermophilus gen. nov., sp. nov., a novel thermophilic manganese- and iron-reducing bacterium isolated from a petroleum reservoir. Int J Syst Bacteriol 1997;47:505–509. [CrossRef]

[28] Dong H, Zhang F, Xu T, Liu Y, Du Y, Wang C, et al. Culture-dependent and culture-independent methods reveal microbe-clay mineral interactions by dissimilatory iron-reducing bacteria in an integral oilfield. Sci Total Environ 2022;840:156577. [CrossRef]

[29] Hamme DJ, Singh A, Ward OP. Recent advances in petroleum microbiology. Microbiol Mol Biol Rev 2003;67:503–549. [CrossRef]

[30] Babaarslan C, Tekeli A, Mehmetoğlu T. Biodegradation of BTEX compounds by a mixed culture obtained from petroleum formationwater. Energy Sources 2003;25:733–742. [CrossRef]

[31] Tüccar T, Ilhan-Sungur E, Muyzer G. Bacterial community composition in produced water of Diyarbakır oil fields in Turkey. Johns Matthey Technol Rev 2020;64:452–465. [CrossRef]

[32] Kaya T. Research of surface active properties of some microorganisms in various industrial wastes. Master Thesis. Ankara Turkey: Biology Department, Gazi University; 2008.

[33] Tüccar T, Ilhan-Sungur E, Abbas B, Muyzer G. Coexistence of sulfate reducers with the other oil bacterial groups in Diyarbakır oil fields. Anaerobe 2019;59:19–31. [CrossRef]

[34] Ibrahim A, Hawboldt K, Bottaro C, Khan F. Review and analysis of microbiologically influenced corrosion: the chemical environment in oil and gas facilities. Corros Eng Sci Technol 2018;53:549–563. [CrossRef]

[35] Wang B, Xin T, Gao Z. Role of HCO_3^- and Cl^- in the pitting of 20CrMo steel in simulated oil field environment. Int J Electrochem Sci 2017;12:7205–7215. [CrossRef]

[36] Asaduzzaman MD, Mohammad M, Islam MM. Effects of concentration of sodium chloride solution on the pitting corrosion behavior of 304L austenitic stainless steel. Chem Ind Chem Eng 2011;17:477–483. [CrossRef]

[37] Liu C, Gong M, Zheng X. Pitting corrosion of 2205 duplex stainless steel at high concentrations of NaCl solution. Int J Electrochem Sci 2018;13:7432–7441. [CrossRef]

[38] Perez TE. Corrosion in the oil and gas industry: An increasing challenge for materials. JOM 2013;65:1033–1042. [CrossRef]

[39] Craig B. Predicting the conductivity of water-in-oil solutions as a means to estimate corrosiveness. Corrosion 1998;54:657–662. [CrossRef]

[40] Gonzalez-Rodriguez JG, Casales M, Salinas-Bravo VM, Albarran JL, Martinez L. Effect of microstructure on the stress corrosion cracking of X-80 pipeline steel in diluted sodium bicarbonate solutions. Corrosion 2002;58:584–590. [CrossRef]

[41] Song W, Zhang J, Li X, Li B, Li F, Fu A. Sulfate Reducting Bacteria Corrosion Component Study of N80 Steel in Simulating Oilfield Produced Water, In: Han Y. editör. Advances in Materials Processing. Lecture Notes in Mechanical Engineering; 2018 Apr; Singapore: Springer; 2018. p. 1187–1194. [CrossRef]

[42] Elumalai P, AlSalhi MS, Mehariya S, Karthikeyan OP, Devanesan S, Parthipan P, et al. Bacterial community analysis of biofilm on API 5LX carbon steel in an oil reservoir environment. Bioprocess Biosyst Eng 2021;44:355–368. [CrossRef]

[43] de Oliveira ESD, Roseana F, Pereira C, Alice M, Lima GDA. Study on biofilm forming microorganisms associated with the biocorrosion of x80 pipeline steel in produced water from oilfield. Mater Res 2021;24:e20210196. [CrossRef]

[44] Wang K, Chen F, Li H, Luo M, He J, Liao Z. Corrosion behavior of l245 pipeline steel in shale gas fracturing produced water containing ıron bacteria. J Chin Soc Corros 2021;41:248–254.

[45] Feng S, Li Y, Liu H, Liu Q, Chen X, Yu H, et al. Microbiologically influenced corrosion of carbon steel pipeline in shale gas field produced water containing CO_2 and polyacrylamide inhibitor, J Nat Gas Sci Eng 2020;80:103395. [CrossRef]

[46] O'Toole G, Kaplan HB, Kolter R. Biofilm formation as microbial development. Annu Rev Microbiol 2000;54:49–79. [CrossRef]

[47] Liu L, Wu X, Wang Q, Yan Z, Wen X, Tang J, et al. An overview of microbiologically influenced corrosion: mechanisms and its control by microbes. Corros Rev 2022; 40:103–117. [CrossRef]

[48] Telegdi J, Shaban A, Vastag G. Biocorrosion-Steel, In: Wandelt K editor. Encyclopedia of Interfacial Chemistry: Surface Science and Electrochemistry; 2018 Feb; Amsterdam, The Netherlands: Elsevier; 2018. pp. 28–42. [CrossRef]

[49] Von Wolzogen Kühr CAH, Van Der Vlugt LS. The graphitization of cast iron as an electrochemical process in anaerobic soils. Water 1934;18:147–165.

[50] King RA, Miller JD. Corrosion by the sulphate-reducing bacteria. Nature 1971;233:491–492. [CrossRef]

[51] Iverson WP, Olson GJ. Anaerobic corrosion by sulfate reducing bacteria due to highly reactive volatile phosphorus compounds. Final report. Available at:

https://www.osti.gov/biblio/5175515 Accessed on Mar13, 2024.

[52] Beech IB, Cheung, CWS. Interactions of exopolymers produced by sulphate- reducing bacteria with metal ions. Int Biodeter Biodegr 1995;35:59–72. [CrossRef]

[53] Enning D, Garrelfs J. Corrosion of iron by sulfate-reducing bacteria: new views of an old problem. Appl Environ Microbiol 2014;80:1226–1236. [CrossRef]

[54] Lv M, Du M. A review: microbiologically influenced corrosion and the effect of cathodic polarization on typical bacteria. Rev Environ Sci Biotechnol 2018;17:431–446. [CrossRef]

[55] Jia R, Unsal T, Xu D, Lekbach Y, Gu T. Microbiologically influenced corrosion and current mitigation strategies: a state of the art review. Int Biodeter Biodegr 2019;137:42–58. [CrossRef]

[56] Tüccar T, Ilhan-Sungur E. Potential Syntrophic Halophilic Partners in Sulfate-Reducing Bacterial Enrichments Derived from Oil Reservoir: Assessment by Sub-culturing Plus Diluting Strategy and Community Analysis. In: Stepec BAA, Wunch K, Skovhus TL, editors. Petroleum Microbiology: The Role of Microorganisms in the Transition to Net Zero Energy. 1st edition. CRC Press Taylor & Francis Group; 2024.

[57] Davey ME, Wood WA, Key R, Nakamura K, Stahl DA. Isolation of three species of Geotoga and Petrotoga: Two new genera, representing a new lineage in the bacterial line of descent distantly related to the “*Thermotogales*”. Syst Appl Microbiol 1993;16:191–200. [CrossRef]

[58] Dahle H, Birkeland NK. Thermovirga lienii gen. nov., sp. nov., a novel moderately thermophilic, anaerobic, amino-acid-degrading bacterium isolated from a North Sea oil well. Int J Syst Evol Microbiol 2006;56(Pt 7):1539–1545. [CrossRef]