International Journal of Ecology and Environmental Sciences 39 (4): 223-230, 2013
ISSN: 0377-015X (Print); 2320-5199 (Online)

The Bio-corrosive nature of Injection Water Sources used in the Nigerian Oil and Gas Industry

C.C. Okoro [1], O.O. Amund [2] and O.B. Samuel [3].

[1] *Dept. of Biological Sciences and Biotechnology, Caleb University, Imota, Lagos, Nigeria. E-mail: chuma2k2001@yahoo.com*
[2] *Dept.of Microbiology, University of Lagos, Lagos, Nigeria (Email: kay_amund@yahoo.com)*
[3] *Dept. of Marine Sciences, University of Lagos, Lagos, Nigeria. (Email: osamuel@unilag.edu.ng)*

ABSTRACT.

The bio-corrosive nature of injection water used in the Nigerian oil and gas industry from different sources such as seawater, produced water, brackish water, fresh and underground water were investigated with special emphasis on some of their components which enhance corrosion such as microbial activity, dissolved oxygen and presence of dissolved substances such as chlorides, sulfates and ammonia. Our investigation reveals that seawater, produced water and brackish water had higher salinity, conductivity, concentrations of dissolved oxygen, TDS, sulfate, organic nutrients, sulphate reducing bacteria (SRB), acid producing bacteria (APB) and higher corrosion rates (0.24-0.56 mm yr^{-1}) than fresh and underground water whose corrosion rates ranged between 0.06-0.08 mm yr^{-1}. Our study also established high correlation between corrosion rates and the concentrations of Fe^{2+}, SRB, APB, TDS, DO and conductivity in all injection water samples examined in the study. The role of microorganisms in enhancing corrosion was also clearly established in some samples.

Key Words: Bio-Corrosion, Injection Water, Microbial Activity, Corrosion Rates, Correlation

INTRODUCTION.

Water injection refers to the method in the oil industry where water is injected back into the oil reservoir usually to increase pressure and thereby stimulate oil production and recovery. Water injection wells are located both onshore and offshore where they are used to increase oil recovery from an existing reservoir. In the Nigerian oil and gas industry, sources of water injection include produced water, sea water, underground water, fresh and brackish waters (OTC 2002). Produced water which is produced along with the oil and gas is either injected into the formation or treated to remove dispersed oil and discharged into the ocean (Okoro 1999). Although the use of produced water reduces the potential risks of formation damage due to incompatible fluids, the risk of scaling and corrosion in injected flow lines and turbings remains (Hills et al. 1987). Seawater is the most convenient source of injection water for offshore production facilities and can also be pumped onshore for use in land fields. Before seawater is used for injection, it must undergo certain processes such as biociding, filtration and deoxygenation to reduce the rate of fouling and corrosion (Hills et al. 1987, Oduola et al. 2009). Underground waters are also used for injection in some onshore oil production facilities in Nigeria and they have the advantage of purity over produced and sea waters and might not require preliminary treatment. Fresh and brackish waters are also used for injection of mainly onshore and near shore locations but they also require biociding and filtration before being used for injection.

Corrosion is defined as the destruction or loss of metal through chemical or electrochemical reactions with the surrounding environment (Bhatia 2009) while bio-corrosion or microbially-induced corrosion (MIC) can be defined as an electrochemical process where the partici-

pation of microorganisms is able to initiate, facilitate or accelerate corrosion by changing the electrochemical conditions at the metal solution interface (Videla and Herrera 2005). About 20-30% of corrosion is related to microbial activity (Fleming 1996, Vidella 1996) but this figure is likely to be higher in Nigerian oil facilities where routine pipeline maintenance is not strictly adhered to in some oil locations that have security challenges (Okoro et al. 2013). MIC poses a serious risk for the integrity, performance and reliability of nearly all metals used in oil and gas operations such as iron, steel, aluminum, copper, titanium and their alloys (Vidella and Herrera 2005). The main types of microorganisms associated with corrosion failures of cast iron, mild and stainless steel structures are sulfate reducing bacteria (SRB), sulfur-oxidizing bacteria, iron- oxidizing and reducing bacteria, manganese-oxidizing bacteria and bacteria secreting organic acids and extracellular polymeric substances (EPS) or slimes (Beech et al. 2000).

Three types of corrosion are common in the oil industry: (a) General corrosion which is characterized by uniform distribution of corrosion over the metal surface; (b) Pitting corrosion which exists only when a small area of the metal corrodes mainly due to dissolved oxygen; and (c) Galvanic attack which occur when two different metals are in contact and the more active one corrodes rapidly. Since injection waters make direct contact with oil pipelines and facilities, their ability to initiate corrosion has been of serious concern to the oil and gas operators and as a consequence, appropriate investigations are usually conducted before water is used for injection purposes.

The components of injection water that are likely to enhance corrosion are: presence of some dissolved solids such as chlorides, sulphates and ammonia and also dissolved oxygen (DO) and microbial activity (Bhatia 2009). Water containing high concentrations of total dissolved solids (TDS) has a high conductivity which provides a considerable potential for galvanic attack and corrosion. Fresh and underground water for instance have low conductivity (low TDS) while seawater has high conductivity (high TDS). Another problem with dissolved solids is that they combine to form highly insoluble mineral deposits on metal surfaces generally referred to as scale (Bhatia 2009, Vidella 1996). Scale in addition to causing physical blockage of pipelines and equipment also reduces heat transfer and increases energy use. Dissolved oxygen is an important electron acceptor in the corrosion of metallic iron and corrosion rate increases with increase in DO (Gedge 1992). Microbial activity is known to promote the formation of corrosion cells and some bi-products of microorganisms such as hydrogen sulphide and ammonia are corrosive (Magot et al. 2000, Voordouw 2011).

We investigated chemical and biological constituents of various injection water sources used in the Nigerian oil and gas industry such as produced water, seawater, fresh water, brackish and underground water. We also determined the corrosion rates of all the injection water sources. An attempt was made to establish the components of the injection water sources that correlate strongly with corrosion rates. The sole aim of the investigation is to establish the bio-corrosive nature of various injection water sources used in the Nigerian oil and gas industry. This will provide baseline information that can be used to guide against frequent cases of bio-corrosion of oil pipelines and facilities in the Nigerian oil and gas industry and elsewhere.

MATERIALS AND METHODS.

Sample Collection and Handling

The injection water samples listed in Table 1 were collected from two offshore, one nearshore and three onshore oil production facilities in Nigeria in sterile 500-mL Nalgene sample bottles. The bottles were filled to the brim to exclude air and preserved with ice bags before transportation to the laboratory for analysis.

Table 1. Sample Codes and Description

Sample Code	Sample description
PWT-OF	Treated produced water from an offshore location
PWT-ON	Treated produced water from an onshore location
PWUT-OF	Untreated produced water from an offshore location
PWUT-ON	Untreated produced water from an onshore location
IW-F	Injection water from a fresh water source
IW-BR	Injection water from a brackish water source
IW-SW	Injection water from a sea water source
IW-UW	Injection water from an underground water source
SDW	Sterile distilled water used as a control

Physicochemical Analysis

Carbonate, bicarbonate, BOD, COD, DO, TOC, Mg^{2+}

and chloride concentrations were analysed as described by Eaton et al. (1995). SO_4^{2-} was analyzed with high performance liquid chromatography (Eaton et al. 1995). Dissolved sulfide was determined using the diamine method (Truper and Schlegel 1964). NH_4^+ was measured using the indole-phenol method while NO_3^-, NO_2^- and organic acids such as Acetate, Propionate and Butyrate were analyzed using HPLC according to the Standard Methods (Eaton et al. 1995). Temperature, conductivity and pH were measured with Orion meters.

Fe^{2+} Assay

Two sets of 13x100 mm tubes were used for analysis. The first set was for acid extraction of the samples where 0.5 mL of 0.5 N HCl was added to each tube followed by the addition of 100 µL of the mixed sample. The mixture was vortexed and allowed to stand for 15 minutes. In the second set, 3 mL of ferrozine solution was added to each tube followed by 100 µL of the acid extracted sample; the sample was vortexed and absorbance was read immediately at A_{562}. Fe^{2}+ concentration in the samples was extrapolated from the standard curve prepared with known Fe^{2+} concentrations as previously described (Eaton et al. 1995).

Measurement of Corrosion Rates

Iron metal coupons of known weight were incubated in water samples for 5 weeks. The corrosion rate (CR) of the liquid samples were determined from the metal weight loss (ΔW) according to the equation: CR= 87,600 x ΔW/(A x T x D) mm/yr as described in Parks et al. (2011), where A represents the coupon area (cm^2) and D represents the density of the steel (7.85g cm^{-3}) and T is the duration of the experiment in hours.

Most Probable Number (MPN) Count

To quantify the presence of sulfate-reducing bacteria (SRB) in the samples, the API RP-38 broth medium was used (Maggot 2005). Serial dilutions of the samples in API RP-38 broth medium were made with the use of a sterile syringe. One mL of each sample was inoculated to the 9.0 mL of the medium and the sequence was repeated serially to the last tube. Samples were then incubated at 37°C for up to 30 days. Formation of black precipitates of iron sulfide was used as a diagnostic tool to confirm the presence of SRB. For acid producing bacteria, prepared ZPRA-5 medium (phenol red-dextrose reagent) with a salinity of 5000 ppm was used. Change in color from orange to yellow shows the presence of acid producers (fermentation of dextrose).

Enumeration of Bacterial Population

An aliquot (0.1mL) of each of the 10-fold serially diluted samples was introduced into prepared nutrient agar plates (Oxoid) in duplicates and incubated at 37 °C for 24 hr, after which colonies of heterotrophic bacteria were observed and counted as previously described (Okoro 1999).

Hydrocarbon-utilizing bacteria in the samples were estimated following the method described by Mills et al. (1978). Iron-reducing bacteria were enumerated by the method described by Nazina et al. (1995).

Statistical analysis

One way analysis of variance (Anova) and Duncan tests were made with a computer statistical package, XPSS 10 to determine the standard deviations, standard errors and the level of correlations between SRB and other factors on one hand and corrosion rates and ferrous iron concentration on the other. Regression analysis was done on Excel software.

RESULTS

Physicochemical Characteristics of Injection Water

Data on physicochemical analyses of samples are shown in Table 2. Produced water samples from offshore and onshore oil production facilities had considerable concentrations of carbonates and bicarbonates as opposed to other injection water sources from the sea, brackish water, fresh water and underground water. Sulfate was also present at considerable levels in all the injection water samples except fresh and underground waters. Hydrogen sulfide gas was not detected in any of the samples. The concentration of ammonium ions were higher in brackish, sea and underground water samples. As expected, samples with higher chloride concentrations such as produced and sea water also had higher conductivity. Organic ions such as acetate, propionate and butyrate were present in considerable concentrations in produced and sea water samples but negligible in fresh, brackish and underground water samples.

Table 2. Results of physicochemical analysis of water samples[a].

Parameter	PWT-OF	PWT-ON	PWUT-OF	PWUT-ON	IW-F	IW-BR	IW-SW	IW-UW
Temp. (ºC) at site	42-58	44-56	38-40	36-45	28-33	26-35	28-34	20-23
pH	6.9-7.1	7.1-7.3	6.8-7.2	7.20-7.30	6.1-6.3	6.3-6.5	6.2-6.3	5.9-6.1
TOC (mg L^{-1})	45-60	28-32	360-380	220-240	15-20	28-36	136-142	6.5-8.2
CO_3 (mg L^{-1})	16-19	28-32	0	16-18	0	0	0	0
HCO_3 (mg L^{-1})	2610-2640	2443-2450	2320-2350	2150-2180	0	23-32	120-132	0
Cl^- (mg L^{-1})	9560-9610	7580-7630	8860-8900	7850-7900	48-63	380-410	10512-10580	36-42
SO_4 (mM)	15.65-16.20	8.50-9.20	13.50-14.30	10.20-10.40	2.65-2.80	12.30-14.50	22.50-32	0
HS^- (mM)	0	0	0	0	0	0	0	0
NO_3 (mM)		0.06	0	0.28	0.14	0	0	0.080
NO_2 (mM)		0	0	0	0	0	0	0 0
Mg^{2+} (mg L^{-1})	0.13-0.16	0.28-0.32	0.4-0.6	0.11-0.16	0.46-0.51	16.50-18.20	23.40-26.30	12.10-14.20
NH_4^+ (mg L^{-1})	1.20-1.28	2.58-2.65	1.35-1.42	0.56-0.65	0.16-0.22	2.80-3.20	1.58-1.70	0.14-0.21
BOD (mg L^{-1})	650-670	840-860	240-255	280-310	20-30	30-45	20-40	10-25
COD (mg L^{-1})	1500-1650	1950-2100	580-600	620-640	160-185	180-210	140-160	80-120
TDS (mg L^{-1})	16,500	14,850	17,620	16870	5700	10,200	18,780	2600
DO (mg L^{-1})	2-5	2-5	4-6	3-5	2-4	3-5	4-6	1-3
Conductivity (S)	22.10	20.60	23.50	21.80	0.56	14.30	24.40	0.21
Acetate (mM)	8.40-8.60	2.80-3.20	1.60-1.80	3.40-3.60	0	0	1.80-1.85	0
Propionate (mM)	1.40-1.56	1.05-1.16	2.30-2.45	1.76-1.80	0	0	0	0
Butyrate (mM)	0.80-1.20	1.30-1.45	0.16-0.20	0.38-0.42	0	0.21-0.48	1.20-1.65	0

a Data represents the ranges observed in triplicate analysis of samples.

Corrosion Rates

Produced, brackish and sea water samples recorded relatively higher concentrations of Fe^{2+} (1.2-2.6 mM) than the underground and fresh water samples (0.28-0.68 mM) as shown in Figure 1. Corrosion rates (CR) followed similar scenario with produced, brackish and sea water samples recording higher corrosion rates (0.24-0.56 mm yr^{-1}) than the underground and fresh water samples (0.06-0.08 mm yr^{-1}) as shown in Figure 2.

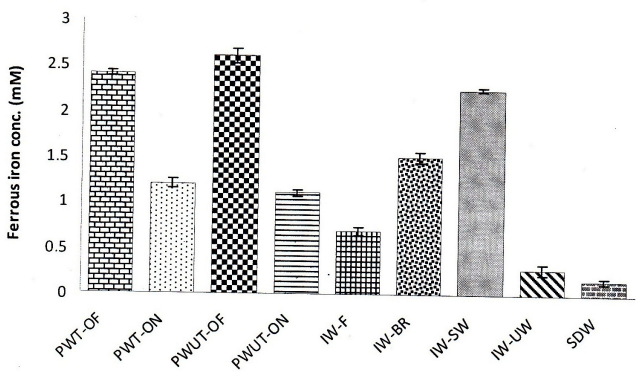

Figure 1. Concentration of Fe^{2+} after 5 weeks of incubation

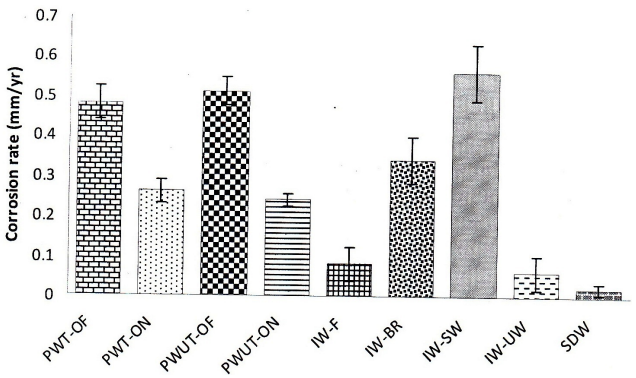

Figure 2. Corrosion rate (mm/yr.) of water samples measured after 5 weeks of incubation.

A comparison of the water samples used in the study showed that higher the corrosion rate, higher are the conductivity and concentrations of SRB and Fe^{2+} (Figure 4). In samples that showed visible evidence of corrosion after 5 weeks of incubation with metal coupons, sulfate was gradually utilized with a corresponding increase in the concentration of SRB, an indication of the implication of SRB in corrosion.

Hydrogen sulfide concentration also increased gradually from week 2 to week 5 when the experiment was terminated (Table 3).

Correlation Between Corrosion Rate (CR) and Other Related Factors

Table 4 shows that the corrosion rate (CR) correlated strongly and positively with concentrations of Fe^{2+} (O.973), SRB (0.910), APB (0.868), Sulfate (0.951), TDS (0.844), conductivity (0.852) and DO (0.758). However there was a poor correlation between corrosion rate (CR) and the concentrations of TOC (0.516) and BOD_5 (0.193). The regression analysis of the correlation between Fe^{2+} concentration and corrosion rate (CR) are shown in Figure 3.

Population Dynamics of Microorganisms Associated with Corrosion

SRB and APB concentrations were relatively higher in produced and sea water samples (10^3 -10^6 cells mL^{-1}) than in fresh, brackish and underground water samples (10^0-10^4 cells mL^{-1}). Iron reducing bacteria were present at relatively higher numbers in brackish water samples (0.053 x 10^5 cfu mL^{-1}) than in produced, sea, fresh and underground water samples (0.011-0.25 x 10^4 cfu mL^{-1}). Heterotrophic and hydrocarbon utilizing bacteria counts were relatively higher in produced water samples than the rest of the samples (Table 5).

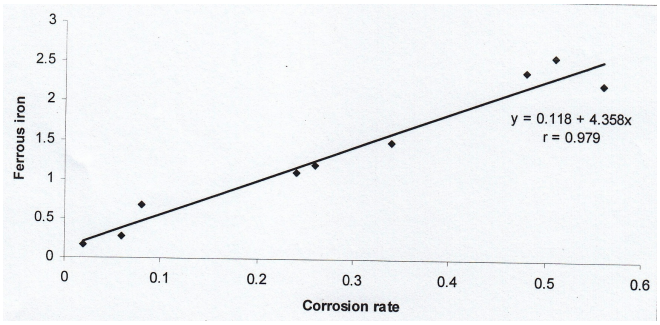

Figure 3. Regression analysis on correlation between Fe^{2+} concentrations and corrosion rate.

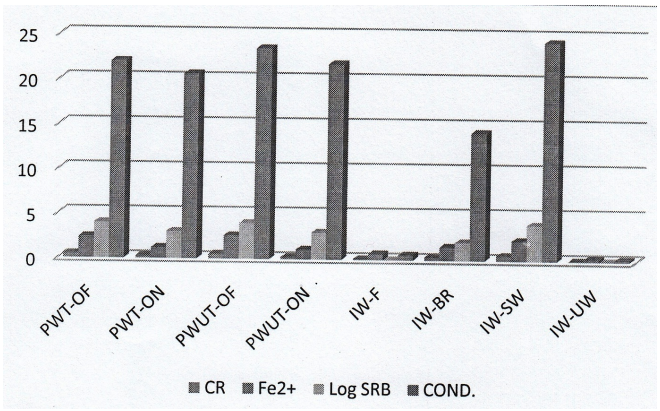

Figure 4. Comparative analysis of samples showing the relationship between corrosion rate, conductivity, SRB and Fe^{2+} concentration in samples.

Table 3. Changes in Sulphate and HS concentrations (mM) and SRB (cells mL^{-1}) in samples which showed visible evidence of corrosion of metal coupons during 5 week incubation

Sample	Week 0			Week 1			Week 2			Week 3			Week 4			Week 5	
	SO_4	HS	SRB	SO_4	HS	SRB	SO_4	HS	SRB	SO_4	HS	SRB	SO_4	HS	SRB	SO_4	HS	SRB
PWT-OF	15.65	0	10^5	12.50	0	10^5	8.10	0.04	10^6	3.60	0.16	10^7	2.40	0.18	10^7	1.20	0.30	10^6
PWT-ON	8.50	0	10^4	7.20	0	10^4	4.80	0.01	10^6	2.80	0.11	10^6	1.20	0.10	10^6	0.60	0.28	10^5
PWUT-OF	13.50	0	10^5	12.20	0	10^5	6.80	0.06	10^6	4.20	0.24	10^7	2.60	0.28	10^7	0.80	0.46	10^7
PWUT-ON	10.20	0	10^4	9.50	0	10^4	7.40	0.01	10^5	4.80	0.06	10^6	2.70	0.16	10^6	2.30	0.18	10^6
IW-BR	12.30	0	10^3	11.70	0	10^3	8.50	0	10^3	6.10	0.03	10^4	3.60	0.06	10^5	2.80	0.03	10^5
IW-SW	22.50	0	10^5	18.80	0	10^5	11.20	0.06	10^6	6.40	0.21	10^7	2.80	0.40	10^7	1.30	0.55	10^6

Table 4. Correlation between Corrosion rate (CR) and other factors in the water samples

	CR	Fe2+	Log SRB	Log APB	S04	TOC	BOD5	TDS	Cond	DO
CR	1.000									
Fe2+	.973**	1.000								
Log SRB	.910**	.888**	1.000							
Log APB	.868**	.850**	.964**	1.000						
S04	.951**	.874**	.876**	.832*	1.000					
TOC	.516	.562	.579	.391	.405	1.000				
BOD5	.193	.247	.484	.608	.124	-.050	1.000			
TDS	.844**	.817*	.972**	.908**	.855**	.625	.446	1.000		
Cond	.852**	.811*	.983**	.951**	.849**	.582	.489	.982**	1.000	
DO	.758*	.750*	.816*	.677	.692	.920**	.098	.842**	.830*	1.000

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 5. Mean population densities of microorganisms found in water samples

Sample	Total Heterotrophic Bacterial Counts (cfu mL^{-1} x 10^5)	Hydrocarbon utilizing bacterial counts (Cfu mL^{-1} x 10^5)	Iron reducing bacteria (Cfu mL^{-1} x 10^5)	SRB Counts (Cells mL^{-1})	APB Counts (Cells mL^{-1})
PWT-OF	3.2	0.0028	0.0016	10^4	10^6
PWT-ON	1.4	0.0056	0.0098	10^3	10^5
PWUT-OF	2.30	0.0011	0.0032	10^4	10^5
PWUT-ON	1.6	0.0033	0.0011	10^3	10^4
IW-F	0.025	0.00012	0.025	0	10^1
IW-BR	0.58	0.00055	0.053	10^2	10^4
IW-SW	0.011	0.00036	0.0045	10^4	10^5
IW-UW	0.015	0.00006	0.008	0	10^1

DISCUSSION .

The results of physicochemical and microbiological analysis clearly indicate that seawater, produced water and brackish water samples recorded higher salinity, conductivity, and concentrations of dissolved oxygen, TDS, sulfate, organic nutrients, SRB and APB than fresh and underground water samples. Some investigators (Bhatia 2009, Vidella 1996) have advanced that the components of injection water that are likely to enhance corrosion are the presence of some dissolved solids such as chlorides, sulfates and ammonia. Corrosion rate is also known to increase with increase in dissolved oxygen because DO is an important electron acceptor in the corrosion of metallic iron (Rompre et al.1998, Gedge 1992). Biproducts of microorganisms such as hydrogen sulfide and ammonia are also corrosive (Magot 2005, Voordouw 2011). These are clear indications that the sea water, produced water and brackish water samples used in the study may be corrosive.

Rim-Rukeh (2005) investigated the corrosion effects of Nigerian produced waters on low carbon steel and found the corrosion rates ranging from 0.077 to 0.370 mm yr^{-1}, based on an exposure time of 120-720 hr. Corrosion of steel coupons in fresh water habitats in Nigeria has also been investigated by Odokuma and Ugboma (2011) who observed that fresh water is not corrosive though carbon steel has a higher corrosion rate than mild steel. In fresh water habitats, microorganisms such as iron bacteria and SRB have been implicated in

corrosion (Pitonzo et al.2007, Lee and Newman 2005) but our study did not produce any clear evidence of corrosion in fresh and underground water samples though the microbiological analysis indicated that iron-reducing bacterial populations were higher in fresh and brackish water samples than in seawater and produced water samples.

Our primary concern was on the role of micro-organisms and their products in enhancing corrosion. The study shows that the residual sulfate was gradually depleted with a gradual increase in the population of SRB and production of hydrogen sulfide up to week 4 when the residual sulfate was significantly depleted and SRB population dropped. This clearly demonstrated that under favorable condition, the indigenous SRB in the water samples can induce corrosion. The role of SRB in pitting corrosion of various metals and their alloys in aquatic and terrestrial environments under anoxic as well as oxygenated conditions has been demonstrated by several authors (Beech et al. 2002, Jack 2000, Park et al. 2011). Other types of bacteria that are associated with corrosion failures of cast iron and stainless steel which recorded relatively high populations in samples with higher corrosion rates are the acid producing bacteria and the iron reducing bacteria.

Our study also demonstrated high correlation between corrosion rate and the concentrations of Fe^{2+}, SRB, APB, TDS, DO and Conductivity. SRB also correlated strongly with APB, sulfate, TDS, conductivity and DO whereas Jack (2002) listed APB and TOC as factors that correlate strongly with SRB for buried pipelines with sulfate correlating poorly. Comparatively, all samples showed high level of relationship between corrosion rate, conductivity, SRB and ferrous iron concentration.

In conclusion, our study demonstrated that injection water sources from produced, sea and brackish water are corrosive while those from fresh and underground water sources are not. The high populations of microorganisms associated with corrosion in some samples and their high correlation with corrosion rates is an indication that bio-corrosion is likely to be largely responsible for most of the corrosion cases in the oil producing facilities sampled. In contrast to the advancement by some authors that 20-30% of corrosion cases are related to microbial activity ((Fleming 1996, Vidella 1996), bio-corrosion episodes in the Nigerian oil production facilities are likely to be higher based on our findings.

ACKNOWLEDGEMENTS

This work was supported by funds from Microcheck (Nigeria) Limited. We thank Oluwaseun Smith from SNEPCO-Nigeria and Leo Echiegile from SPDC, Nigeria, for providing us with all the injection water samples used in the analysis.

REFERENCES

Beech, I.; Bergel, A.; Mollica, A.; Flemming, H.C.; Scotto, V. and Sand, W. 2000**.** Simple Methods for the Investigation of the Role of Biofilms in Corrosion. Brite-Euram 111 Thematic network (No: BRR7-CT98-5084). John Wiley, New York. 27 pages.

Bhatia, A. 2009. Cooling Water Problems and Solutions. Project No. M05-009. Continuing Education and Development Inc., New York. 45 pages..

Eaton, A.D.; Clesceri, L.S., and Greenberg, A.E. 1995. Standard Methods for the Examination of Water and Waste Water. 19th Edition. United Books Press, Batimore, MD. 1126 pages.

Fleming, H.C. 1991**.** Biofilms as a particular form of microbial life. Pages 3-9, In: Fleming, H.C. and Geesey, G.G. (Editors). Biofouling and Biocorrosion in Industrial Water Systems. Springer, Heidelberg.

Gedge, G. 1992. Corrosion of cast iron in portable water service. Proceedings of the Institute of Materials Conference, London, UK.

Hill, E.C.; Shenman, J.L and Watkinson, R.J. 1987. Microbial Problems in Offshore Oil Industry. John Wiley, Chichester, U.K. 257 pages..

Jack, T.R. 2002. Biological corrosion failures. In: Failure Analysis and Prevention, ASM handbook volume 2. pages. 881-890. ASM International, Materials part, Ohio, USA.

Lee, A.K. and Newman, D.K. 2005. Microbial iron respiration. Impacts on Corrosion processes. Applied Microbiology and Biotechnology 62: 134-139.

Maggot, M. 2005. Indigenous microbial communities in oil fields. Pages 21-34, In: Ollivier, B. and Maggot, M. (Editors) Petroleum Microbiology. ASM Press, Washington, DC.

Nazina, T.N.; Ivanova, A.E.; Golubeva, O.V.; Ibatullin, R.R.; Belyaev, S.S. and Ivanov , M. V. 1995. Occurrence of sulfate and iron reducing bacteria in stratal waters of the Romashkinskoe Oil Field. Microbiology (New York) 66: 203-208.

Odokuma, L.O. and Ugboma, C.J. 2012. Microbial corrosion of steel coupons in a fresh water habitat in the Niger Delta. Journal of Ecology and Natural Environment 4(2): 42-50.

Oduola, L.; Igwebueze, C.; Dede, A; Braimoh, L and Keedak, T.O. 2009. Reservoir souring mitigation in the Bonga WestAfrican deep water field using Calcium nitrate. Presentation at the 2009 International Conference, Workshop and Exhibition on Biotechnologies for Improved Production of Oil and Gas in the Gulf of Guinea. April 1-3, Abuja, Nigeria.

Okoro, C.C. 1999. Microbial Degradation of Hydrocarbons in Produced Water from Crude Oil Production Operations in Escravos Tankfarm. Ph.D. Thesis. University of Lagos, Nigeria 269 pages..

Okoro, C.C.; Amund, O.O. and Samuel, O.B. 2013. Biologically active solid deposits in biocide treated oil and gas pipelines from a Nigerian onshore oil production facility International Journal of Ecology and Environmental Sciences 39(1): 51-58.

OTC. 2012. Focus on the Nigerian Oil and Gas Industry. Offshore Technology Conference. Houston Texas. 87 pages..

Park, H.S.; Chatterjee, I.; Dong, X.; Wang, S.; Sensen, C.W.; Caffrey, S.M.; Jack, T.R.; Boiven, J. and Voordouw, G. 2011. Effect of Sodium bisulfite injection on the microbial commu-nity composition in a brackish water transport pipeline. Applied and Environmental Microbiology 77 (19): 6908-6917.

Pitonzo P.J.; Amy P. and Castrol, J.P. 2007. Microbially influenced corrosion. Corrosion 60: 64-74.

Rim-Rukeh, A. 2005. Physico-chemical analysis and corrosion effect of produced water on low carbon steel. Global Journal of Pure and Applied Sciences 11 (4): 511-515.

Rompre, R.R.; Prevost, M.; Morisette, C. and Lafrance, P. 1998. Selecting the best corrosion control strategy using a near rapid corrosion monitoring tool. Proceedings of AWWA Water Quality Technology Conference, Paper 5c. San Diego, CA.

Truper, H.G, and Schlegel, H.G. 1964. Sulphur metabolism in Thiorhodaceae. I. Quantitative measurements in growing cells of *Chromatium okenii*. Antonie van Leeuwenhoek 30: 225-238.

Videla, H. A. 1996. Manual of Biocorrosion. CRC Press, Boca Raton, FL. 273 pages.

Videla, H.A and Herrera L.K. 2005**.** Microbiologically influenced corrosion: Looking to the future. International Microbiology 8(3): 169-180.

Voordouw, G. 2011. Production Related Petroleum Microbiology: Progress and Prospects. Current Opinion in Biotechnology 22: 1-5.

Received 4 June 2013;
Accepted 19 November 2013