

Full Length Research Paper

Bio-corrosion of water pipeline by sulphate-reducing bacteria in a mining environment

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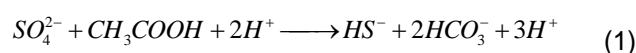
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Detrimental effects of corrosion in conjunction with bacterial activity in water pipeline systems have led to an increase in research in how to prevent such occurrences. In particular, sulphate-reducing bacteria (SRB), found in anaerobic conditions underneath the main corrosion shell, are noteworthy for their effects in promoting localized corrosion. This study investigates the presence of SRB in water, in a water pipeline and in the soil near the pipeline at a mining operation, under conditions that would be expected to be stable toward corrosion. Samples of water in pipes showed a high frequency of SRB. Cast iron coupons placed in pipes gave positive results for SRB colonization after only one month. Corrosion rates of the coupons increased in the presence of SRB, indicating microbially induced corrosion. Application of various biocides to control SRB was evaluated.

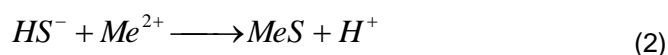
Key words: Sulphate-reducing bacteria, corrosion, water pipeline, biocide.

INTRODUCTION

Sulphate-reducing bacteria (SRB) are one group of anaerobic prokaryotes. The main genus of SRB is *Desulfovibrio*. *Desulfovibrio desulfuricans* is often used to immobilize dissolved heavy metals as metallic sulfides. Beijerinck (1895) showed that living matter could reduce sulphate to sulphide in sediments under anaerobic conditions. Although many bacteria can produce sulphide, only a few do so at a sufficient rate for application in high-rate processes. SRB are nonpathogenic (that is, they are not capable of causing disease) and they are anaerobic bacteria (that is, they require an oxygen free aqueous environment). These rapid sulphide-generating bacteria are able to conserve energy by the reduction of sulphur oxyanions (Widdel and Hansen, 1992). A typical overall conversion is shown in equation 1 (neglecting the small amount of organic material required to produce biomass):



Eight electrons are transferred from the energy source acetic acid to the electron acceptor sulphate to produce sulphide. The reaction equation shows that in the same process, alkalinity is also produced. This leads to an increase in the pH of the water, often to a near neutral value. Typically, a certain amount of metals is present together with the sulphate. These metals will react with the dissolved sulphide to form highly insoluble metal sulphides (Equation 2).



Me²⁺ can, for example, be copper, zinc etc. Combining the action of sulphate reduction by SRB and

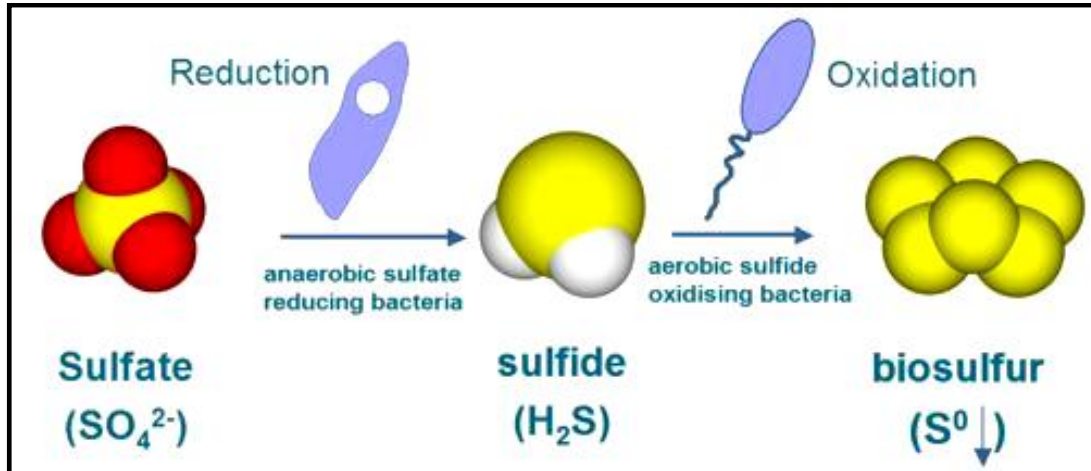


Figure 1. Combining the action of SRBs and sulfide oxidizing microbes (to the left - one SRB bacterium with elemental sulfur particles on the cell membrane)

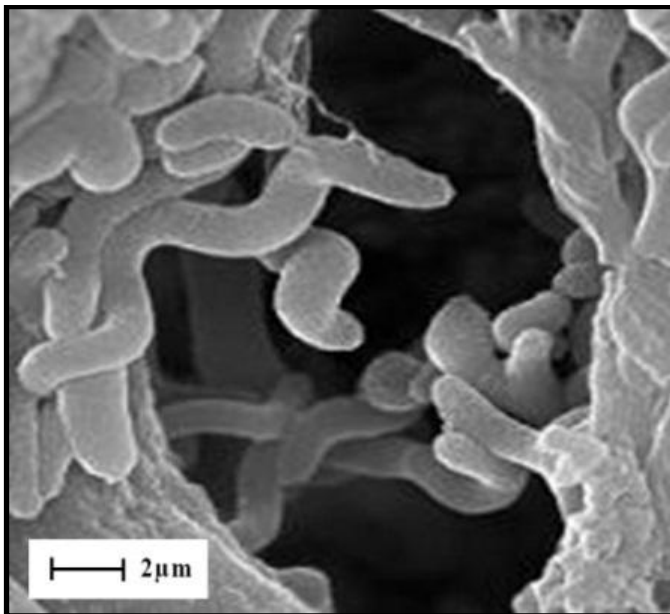


Figure 2. SRB culture with a carbonate precipitate (the bacteria are about 6 to 8 μm long and 2 μm in diameter).

sulphide oxidation by sulphur-oxidising microbes is presented in Figure 1. Carbonate precipitation by SRB is shown in Figure 2.

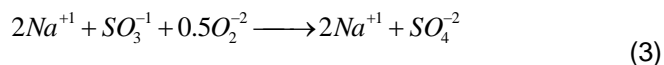
The effluents produced in sulphide ore mines, defined as acid mine drainage (AMD), also contain large amounts of heavy metals. Mining and industrial drainage containing sulphate and heavy metal negatively affects terrestrial and aquatic ecosystems in several countries around the world. SRB can be used to biologically treat metal- and sulphate-rich waste water, reducing sulphate to sulphide to precipitate metal sulphides. In AMD treatment processes, this chemically stabilizes the toxic metal ions

as solid metal sulphides (Zagury et al., 2006). Furthermore, SRB produce carbonate (equation 1) which increases the pH.

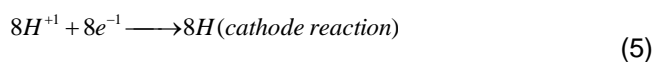
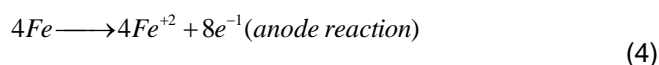
Conversely, a detrimental aspect of the activity of SRB is metal corrosion. The incidence of SRB colonizing ferrous water mains has been reported for many years (Butlin, 1949; Tuovinen et al., 1980; Beech et al., 1994). These bacteria are generally associated with the area underneath the main corrosion shell since they require anaerobic conditions (Butlin, 1949; Beech et al., 1994). However, anaerobic conditions may also occur on the corrosion surface due to the presence of other aerobic bacteria producing anoxic pockets (Spencer, 1971; Gaylarde, 1989; Jain, 1995). Once colonization has begun, bacterial growth is further promoted due to the spread of reducing conditions (Starkey, 1958). SRB are particularly unwanted in ferrous mains because of their notable effect in promoting corrosion by reducing sulphate to sulphide, which may in turn oxidize hydrogen to hydrogen sulphide, and this may react further to produce ferrous sulphides or sulphuric acid, which also contributes acid corrosion (Starkey, 1958; Gaylarde, 1992). In addition, the undesirable "rotten egg" smells of hydrogen sulphide, and the possibility of sloughing of the black slime, can lead to consumer complaints and increased health risks. Microbial corrosion by SRB results in severe graphitization of cast iron, leaving a soft surface liable to collapse (Butlin, 1949; Starkey, 1958; Seth and Edyvean, 2006).

SRB are capable of causing severe corrosion of iron material in a water system because they produce enzymes which have the power to accelerate the reduction of sulphate compounds to the corrosive hydrogen sulphide, thus SRB act as a catalyst in the reduction reaction. However, in order for this reduction to occur, four components must be present. That is, SRB must be present, sulphates must be present, an external energy

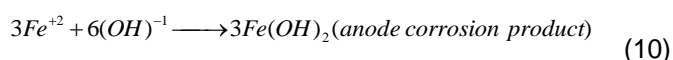
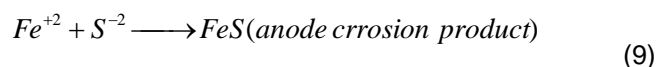
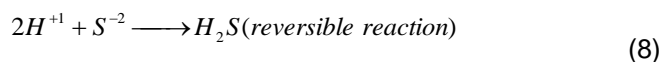
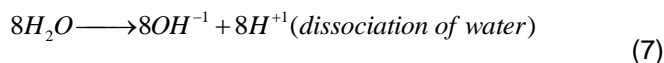
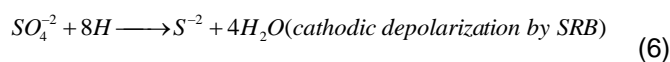
source in the form of free electrons must be present, and the temperature of the water must be less than approximately 65°C (150°F). A water system may naturally contain sulphate based compounds. Another source of sulphate originates from sulphite added to a closed water system as an oxygen scavenger and corrosion inhibitor. The sodium sulphite is oxidized to sodium sulphate as indicated in reaction 3 below.



Excess electrons occur in a water system as a result of iron corrosion at the anode and cathode cells as indicated in reactions 4 and 5 below.



The resultant accelerated corrosion mechanism of iron by SRB is illustrated in equations 6 to 10 below.



Microbiologically influenced corrosion (MIC) is the damage caused or accelerated by the presence of bacteria and other microorganisms and their metabolic activities on metals and alloys. Many types of bacteria, including sulphate-, iron- and CO₂⁻ reducing bacteria, sulphur-, iron- and manganese-oxidizing bacteria are associated with the MIC of metals and alloys (Beech and Sunner, 2004; Anandkumar et al., 2009). Among them, SRB are recognized as a major group involved in anaerobic corrosion. These latter microorganisms can coexist in naturally occurring biofilms with a wide bacterial community, including fermentative bacteria, often forming synergistic communities (consortia) that are able to influence electrochemical processes through cooperative metabolism (Beech and Gaylarde, 1999). The sulphate reductive activity of SRB is thought to account for >75% of the corrosion in productive oil wells, and for >50% of the failures of buried pipelines and cables (Walch, 1992).

SRB are strictly anaerobic microorganisms responsible for the terminal mineralization of organic matter in anoxic environments. They are a diverse group of prokaryotes that may be divided into four groups based on r-RNA sequence analysis: Gram-negative mesophilic SRB, Gram-positive spore-forming SRB, thermophilic bacterial SRB and thermophilic archaeans (Castro et al., 2000). A majority of studies on SRB in oil-field environments have concentrated on the ecology and physiology of mesophilic microorganisms, which grow optimally between 20 and 40°C (Anandkumar et al., 2009).

One of the important practical problems is the control of SRB growth in economically important situations in the petroleum sector. Consequently, considerable research has been devoted to testing various potential micro-biocides (Kumaraswamy et al., 2010).

SRB, which generate large amounts of toxic hydrogen sulfide in aquatic ecosystems, are important not only for ecological reasons but also economically. The activities of SRB in natural and manmade systems are of great concern to engineers in many different industrial operations (Gibson, 1990; Odom, 1990; Odom and Singleton, 1992).

Oil, gas and shipping industries are seriously affected by the sulfide generated by SRB (Battersby, 1988; Hamilton, 1994; Peng et al., 1994; Okabe et al., 1995; Cullimore, 2000). In the oil industry most monitoring of micro-biologically influenced corrosion (MIC) has been conducted by cultivation based techniques (Ghazy et al., 2011). The production of H₂S often indicates the activity and presence of sulphate-reducing microorganisms in natural habitats. The presence of H₂S is obvious by its characteristic smell, black precipitation of ferrous sulfide when iron minerals are present. As a result of SRB metabolism, reduced sulphur compounds can impair water quality, making for unpleasant odour, and also can contribute to biological contamination of well filters (Wargin et al., 2007).

The aim of this study was to evaluate the activity of SRB on the corrosion of the water pipelines located in the Sarcheshmeh copper mine. Also, application of various biocides to decrease numbers of SRB and the corrosion resulting from their activity was investigated.

MATERIALS AND METHODS

Sampling and analysis of corrosion products

To study microbial corrosion potential of water inside the pipeline and surrounding soil, samples were taken from 16 water wells inside and around the Sarcheshmeh copper mine. A total of 96 water samples were analysed. Also, 10 soil samples were collected near the water pipes from various depths between 1 to 2.5 m.

A qualitative test was performed to detect the presence of FeS, an indicator of SRB activity. The test involved addition of a few drops of hydrochloric acid to corrosion products on pipe samples. When hydrochloric acid contacts FeS, H₂S is produced and is readily identified from its distinctive, unpleasant odor.

Mineralogical determinations were made using x-ray diffraction (XRD) while atomic absorption spectroscopy (AAS) and induced

Table 1. The composition of Postgate API medium.

| Composition | Value (g/l) |
|--|-------------|
| MgSO ₄ . 7 H ₂ O | 0.2 |
| KH ₂ PO ₄ (anhydrous) | 0.01 |
| Fe(SO ₄) ₂ (NH ₄) ₂ .6H ₂ O | 0.2 |
| NaCl | 10 |
| Sodium lactate | 3.5 |
| Yeast extract | 1 |
| Ascorbic acid | 0.1 |
| Thioglycollic acid | 0.1 |
| FeSO ₄ .7H ₂ O | 0.004 |
| Agar | 15 |
| Distilled water | 1000 ml |

Couple plasma (ICP) was used for qualitative analysis.

Table 2. Classification of corrosive environment using TBC factor (cells/mL).

| Corrosive environment | TBC |
|------------------------|----------------------------------|
| Low level corrosive | 10 ³ |
| Medium level corrosive | 10 ³ -10 ⁵ |
| High level corrosive | >10 ⁵ |

Sulphate-reducing bacteria (SRB) and total bacteria counts (TBC) tests

Sulphate-reducing bacteria (SRB) culturing procedure

The bacterial culture medium used in these experiments was Postgate API which is widely used by the oil and gas industry (Table 1).

Also, for proper cultivation of SRB, the process in four stages was carried out as follows: A, A 10cc aliquot of the sample was taken using a syringe; B, the sample inside the syringe was injected into sterile anoxic culture medium; C, the container with the inoculated culture medium was maintained at room temperature for 21 days; D, all the samples were observed at a fixed time every day. Changes in the clarity of the medium, or development of black spots (FeS) which confirmed the presence of SRB bacteria in the sample, were noted.

Procedure for total sulphate-reducing bacteria (SRB) count total bacteria counts (TBC)

Standard culture medium API was used in the following process:

A, the lid of container of the culture medium was removed; B, water sample was added to culture glass containing the medium; C, after 1 min, water content of the glass was discharged and the lid was closed; D, container including culture medium was inoculated at room temperature; E, after 48 h, the total number of bacteria was counted; F, if the total bacteria counts (TBC) in the environmental sample was higher than 10⁵/ml, the effect on corrosion was judged to be high (Table 2).

Tests with biocides

The amount of biocide injected into the water was set at 100 mg/L. In all tests, 10 g of biocide was used in 100 L of water. Coupon (carbon steel) dimensions used in these experiments were 0.16 × 1.27 × 7.63 cm with 22 cm² area. The pH was measured using a pH meter (MP120 model, Mettler Toledo Company, Switzerland) and Eh meter was used for measuring the oxidation reduction potential (826pH mobile model, Metrohm Company, Switzerland). The Eh meter consists of a platinum electrode and a silver/ silver chloride reference electrode in KCl solution.

Polarization tests

The steel coupons used in the biocide tests (Corrosion rate measurements section) were immersed in water for 30 days for polarization tests. Polarization tests were carried out using potentiodynamic method with potentiostat EG and G, Model 263A and FRA EG and G Model 1025 with Easy Corr and Excel programs. Scan rate and potential were set to 1 mV/s and ± 400 mV respectively and then the electrode was put inside the water sample containing 100 mg/L biocide for a week. The working electrode was prepared from the same carbon steel as the water pipeline (1 × 1 cm).

Corrosion rate measurements

The corrosion rate inside the water pipeline was determined using the following two methods: A) the coupon setting method; B) corrater device.

The coupon setting method in water and soil

This method is based on the measured weight loss of metal samples. Dimensions of steel coupons were as follows: A) 0.16 × 1.27 × 7.63 cm (area: 22.2 cm²); B) 0.12 × 0.9 × 7.5 cm (area: 15.5 cm²)

The steel coupon (A) was used in the experiments. To determine the corrosion rate of the samples the following formula was used:

$$mpy = ([M_1 - M_2] \times 3650 \times 1000) / (P \times A \times D \times 25.4) \quad (11)$$

Where, M₁, is the initial sample weight (g), M₂ is the secondary sample weight (g), P is the sample density (gr/cm³), D is the number of days and A is the sample surface (cm²).

To estimate the corrosion rate, coupon setting method was carried out inside the water pipeline using steel coupon with ASTM standard dimensions (0.16 × 1.27 × 7.63 cm) for 30 days and then the coupon was fixed at a special place using a Teflon holder parallel to the water flow direction. The corrosion rate was calculated using the weight loss method according to the mentioned formula/equation (11). For determination of the corrosion rate of the soil around the pipe, two coupons with dimensions (0.1 × 2 × 2 cm and area 8.8 cm²) were used for one month. These coupons were set at a depth of 40 cm from ground level and 50 cm from each other (interval distance). One of the coupons was covered by plastic as control test and the other was placed in soil around the pipe directly and without any coverage. After removal of the coupons from water or soil, they were washed by distilled water and hydrochloric acid solution for one minute and washed with distilled water again and then finally dried and weighted. Corrosion rate can be estimated with amount of weight loss of coupons during exposure in the environment.

Table 3. Average six months analysis of the water in pipeline in the Sarcheshmeh mine.

| Component | Value |
|-------------------------------|------------------|
| TDS | 208 ppm |
| pH | 7.6 |
| O ₂ | >100 ppm |
| SO ₄ ²⁻ | 77ppm |
| SiO ₂ | 85 ppm |
| Cl ⁻ | 35 ppm |
| Conductivity | (μ s/cm)501 |

Table 4. Chemical analysis of the pipeline (steel) in the Sarcheshmeh mine.

| Component | Value |
|-----------|-------|
| S | 0.05 |
| P | 0.04 |
| Mn | 1.15 |
| C | 0.27 |

Table 5. XRD analysis of the corrosion sediment in different location.

| Sample location | Mineral/phase | Chemical formula |
|---|---------------|--------------------------------|
| Upper level of sediment | Limonite | FeOOH. nH ₂ O |
| | Magnetite | Fe ₃ O ₄ |
| Middle of the sediment | Limonite | FeOOH. nH ₂ O |
| | Magnetite | Fe ₃ O ₄ |
| Lower level of sediment (Near of the pipeline) | Magnetite | Fe ₃ O ₄ |
| | Limonite | FeOOH. nH ₂ O |

Corrater device

Corrater is an electronic device for detecting corrosion in water systems which can be used to measure the corrosion rate directly. The corrosion measurement in corrater is based on the linear polarization resistance. In this method, the oxidation reaction occurs at the anode and the cationic reduction reaction takes place at the interface of fluid and the pipe at the cathode area.

RESULTS AND DISCUSSION

Pipeline water chemistry

The water in the pipeline at Sarcheshmeh mine was slightly alkaline, low in chlorides and contained sulphate,

which could serve as an electron acceptor for SRB and therefore is potentially reducible to H₂S (Table 3).

Characterization of corrosion product

The water pipeline at Sarcheshmeh mine was composed of mild steel. The minor components of the pipe included S, P, Mn and C (Table 4).

The corrosion product formed on the internal surface of the pipeline consisted of limonite and magnetite as characterized by X-ray diffraction (XRD) and chemical analysis methods (Table 5 and Figures 3 and 4).

As shown in Table 3, all trivalent iron oxide is formed on the surface and bivalent iron oxide occurred below the rust layer. FeS often is an important phase in corrosion products, but in this case, the dominance of other minerals (Table 5) resulted in FeS not being detected by XRD. Nonetheless, the high amount of sulfur in the corrosion product (16.15%) (Figure 4), and liberation of hydrogen sulfide by hydrochloric acid (hydrochloric acid test and optical microscopic study section), indicates the presence of FeS and that corrosion in the water pipeline could be caused by SRB. The presence of phosphorus in the corrosion products (Figure 4) also has been reported previously; are active, phosphorus compound produced by SRB may be involved in bio-corrosion of iron and steel (Iverson and Olson, 1983).

Hydrochloric acid test and optical microscopic study

A corroded part of the pipeline was examined using a hydrochloric acid test and light microscopy analysis to determine if SRB may be involved in corrosion of the pipe. After polishing of the pipe, a metallographic study was carried out under an optical microscope and several holes and cavities were found on the surface which is illustrated in Figure 5.

Microbial corrosion is always local, (that is, the type is a gap or hole in the pipe) and after addition of a few drops of hydrochloric acid on the black parts of specimens identified in Figure 6, a strong odor of H₂S was detected.

Direct counts of sulphate-reducing bacteria (SRB)

Numbers of SRB in water well no.6 and 16 which were located in the Sarcheshmeh region and also the water main pipeline in the copper mine and the soil around the pipe are given in Table 6. The number of SRB in a soil environmental sample was 4.5×10^6 /ml. It can be concluded that due to higher number of soil SRB compare to other environments, highest corrosion process was observed. No SRB were detected in water samples containing various biocides. It showed that all biocides can destroy SRB effectively, but the efficiency of their operation is different. The SRB bacteria was observed by micro-biological microscope which its shape

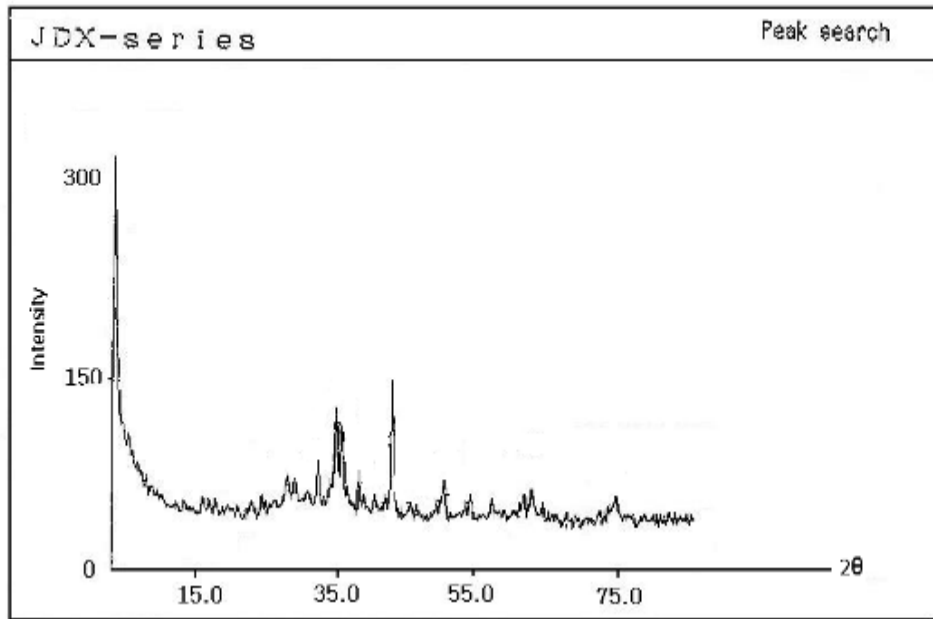


Figure 3. XRD pattern of the corrosion product.

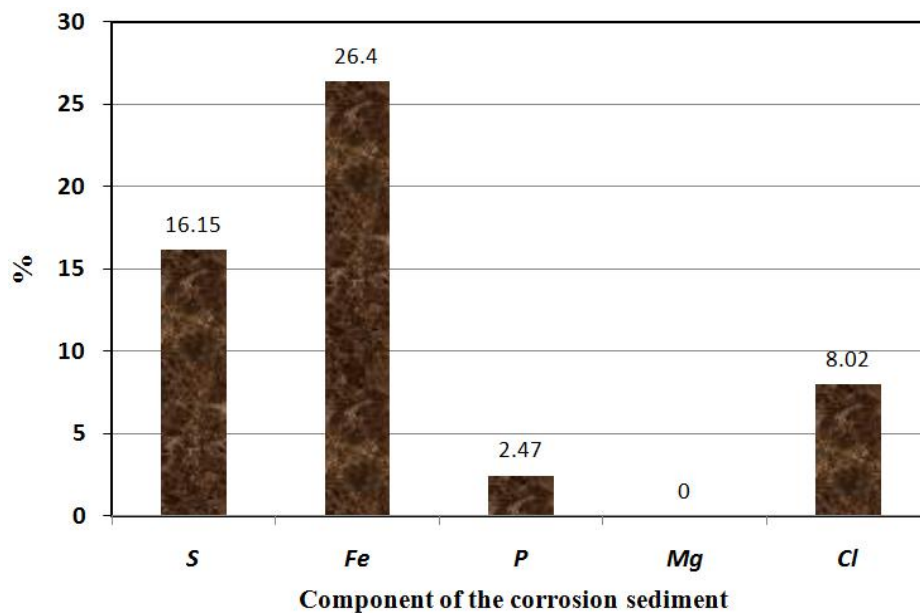


Figure 4. Component of the corrosion product in element forms

and colony in the culture medium are presented in Figure 7.

Corrosion measurement methods (coupon setting and Corratere device)

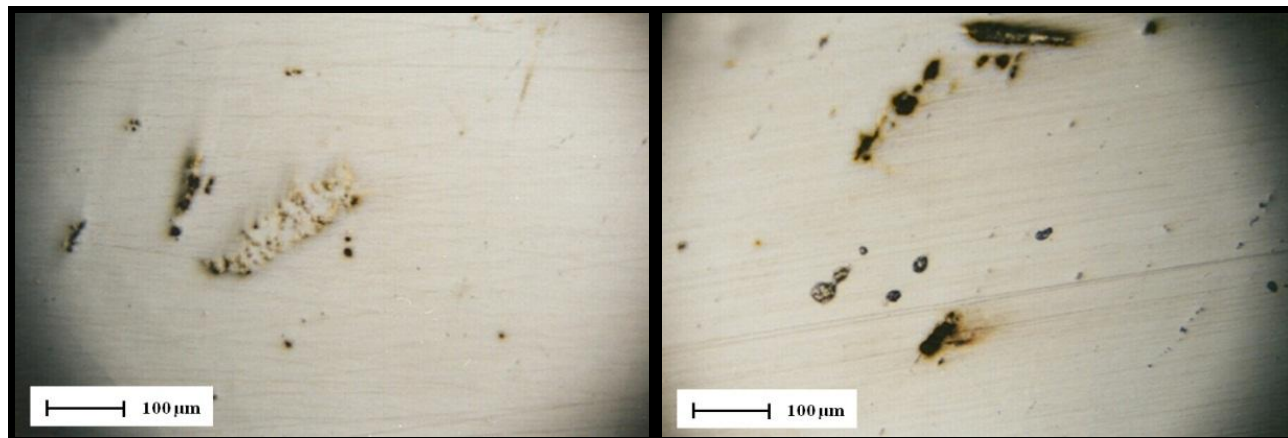
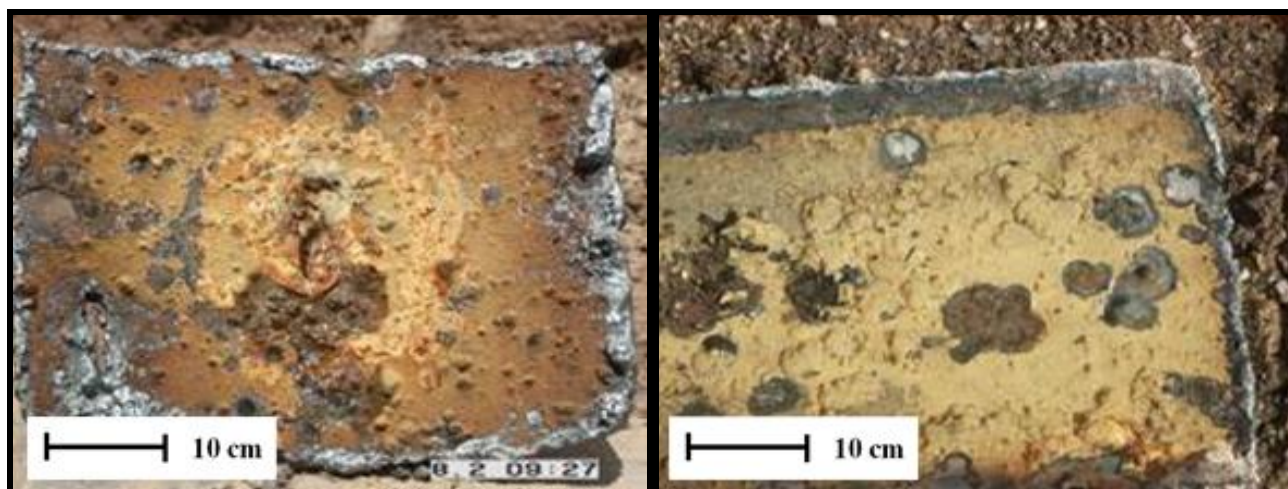
Corrosion rate of water in water pipe using Corratere

device and coupons setting and soil around the pipeline by coupons setting method were investigated (Table 7). It should be mentioned that for measurement of the corrosion rate, weight loss method (mpy) was used.

Results from the Table 7 show that corrosion rate of coupons in soil around the pipe was two times higher than water inside the water pipe, therefore cathodic protection of pipe in soil and application of the appropriate

Table 6. Number of SRB bacteria in different places with corrosion level of coupons

| Environment | Count of SRB (in ml.) | Corrosion level |
|----------------------|-------------------------|-----------------|
| Soil | $10^6 \times 4.5 \cong$ | Very severe |
| Water, well No.16 | $10^6 \times 1.5 \cong$ | High |
| Water, well No.6 | $10^6 \times 1.2 \cong$ | High |
| Water, Main pipeline | $10^5 \times 1.5 \cong$ | Medium |
| Water with biocides | Not seen | None |

**Figure 5.** Presence of cavity on the surface of water pipeline (Optical microscopy).**Figure 6.** Hydrochloric acid test on the dark color corrosion product.

coating is necessary and important. Corrosion rate of water was detected using above two methods (coupon setting and Corraters devices), but due to based works (principle) of the Corraters which is linear polarization resistance, the corrosion rate was measured by more accuracy.

Inhibitors performance on the water pipes

Biocide CWT110 had best performance with lowest corrosion rate (0.743 mpy) and Biocide MBA4517 had weakest efficiency with highest corrosion rate (2.445 mpy) (Table 8). The visual appearance of the coupons

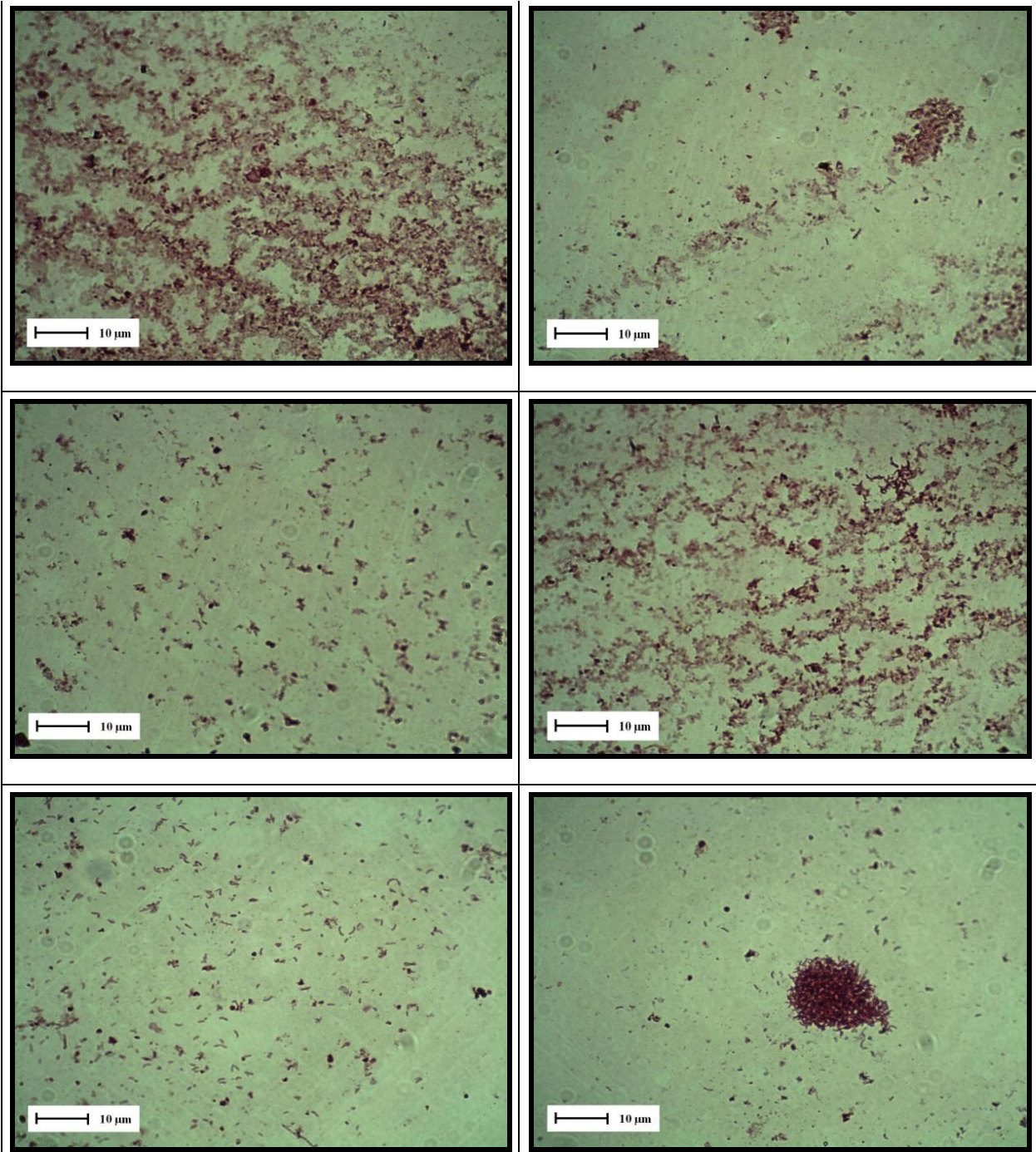


Figure 7. SRB bacteria and its colony (inoculated in the culture medium).

after one month was consistent with their extent of corrosion; the coupons with biocide CWT110 had best appearance after this period of time (Figure 8). The order of different biocide performance is as below:

ISOcwt5> MBA8115> MBA4517>CWT15> MBA8120>
MBA8110>CWT110

pH and Eh of water with different biocides

In this experiment, 0.5 L of water containing various biocides was taken and Eh and pH values were measured (Table 9). The effect of water on iron corrosion in pH = 4.3 to 10 was low. Due to reduction of sulfate to sulfide, corrosive water containing SRB bacteria has

Table 7. Corrosion rate of water and soil around the pipeline.

| Environment | Coupon characteristic | | | | Coupon setting period (day) | Density (g/cm ³) | Corrosion rate | |
|-------------|-------------------------|--------------------|----------------------|-----------------|-----------------------------|------------------------------|---------------------|-----------------------|
| | Area (cm ²) | Primary weight (g) | Secondary weight (g) | Weight loss (g) | | | Coupon method (mpy) | Corrater device (mpy) |
| Soil | 8.8 | 37.6312 | 37.5110 | 0.1201 | 30 | 7.86 | 8.32 | - |
| Water | 22 | 10.6037 | 10.4481 | 0.1555 | 30 | 7.86 | 4.31 | 4.82 |

Table 8. Biocide performance on the water pipes.

| Biocide | Primary weight (g) | Secondary weight (g) | Weight loss (g) | Density (g/cm ³) | Coupon setting method | |
|---------|--------------------|----------------------|-----------------|------------------------------|-----------------------|----------------------|
| | | | | | Period (day) | Corrosion rate (mpy) |
| CWT110 | 10.5572 | 10.5304 | 0.026 | 7.86 | 30 | 0.743 |
| MBA8110 | 10.5904 | 10.5576 | 0.032 | 7.86 | 30 | 0.906 |
| MBA8120 | 10.5422 | 10.4938 | 0.048 | 7.86 | 30 | 1.338 |
| CWT15 | 10.5829 | 10.5298 | 0.053 | 7.86 | 30 | 1.481 |
| ISOcwt5 | 10.5802 | 10.5179 | 0.062 | 7.86 | 30 | 1.737 |
| MBA8115 | 10.5802 | 10.5055 | 0.074 | 7.86 | 30 | 2.069 |
| MBA4517 | 10.5222 | 10.4339 | 0.083 | 7.86 | 30 | 2.445 |

Table 9. Eh (mV) and pH values for water containing various biocides.

| Biocide | pH | E _h | Oxidizer or non-oxidizer | Component |
|-----------------|------|----------------|--------------------------|--------------------------------------|
| CWT110 | 8.9 | 173 | Non-oxidizer | <i>Isothiazolin</i> |
| MBA8110 | 8.72 | 178 | Non-oxidizer | <i>Isothiazolin</i> |
| MBA8120 | 8.71 | 182 | Non-oxidizer | <i>Quaternary ammonium compounds</i> |
| CWT15 | 8.57 | 194 | Non-oxidizer | <i>Metronidazol</i> |
| ISO CWT5 | 8.49 | 196 | Non-oxidizer | <i>Metronidazol</i> |
| MBA8115 | 8.23 | 201 | Non-oxidizer | <i>Quaternary ammonium compounds</i> |
| MBA4517 | 8.12 | 205 | Non-oxidizer | <i>Carbamate</i> |
| Corrosive water | 8.2 | 350 | - | <i>SRB</i> |

maximum Eh (350 mV) with lowest pH value (8.2). In water containing different biocides, biocides prevent setting of the reaction and consequently, Eh of the environment was maintained at lower value and pH reached to maximum its value. Biocide with best prevention performance had lowest Eh and highest pH, therefore biocide CWT110 which is classified in isothiazolin group had best efficiency to eliminate SRB bacteria from the water in the water pipeline.

Scanning electron microscopy (SEM) study

Scanning electron microscopy (SEM) was used to investigate the surface of the steel coupons that had been placed under the various corrosive conditions. The surface of the normal steel showed no holes or cavities or

corrosion products (Figure 9a). The surface of a coupon which was set in 1.5 m depth of the soil near the pipeline for 30 days had more holes and corrosion products on the surface (indicated as dark and light spots) indicating corrosive conditions (Figure 9b). The corrosion rate of this coupon was 8.32 mpy (Table 7). There was also a corrosive environment in water of the water pipeline (Figure 9c) but less than the soil. The corrosion rate reached 4.31 mpy. In water containing different biocides (Figure 9d, 9e and 9f), the surfaces of coupons contained fewer pits and corrosion products. These observations were consistent with corrosion rates (Table 8) which were 2.44 mpy for biocide MBA4517, 1.338 mpy for biocide MBA8120 and 0.743 mpy for biocide CWT110. The corrosion rate data and SEM images suggest biocide CWT110 could substantially reduce biocorrosion in the pipeline.

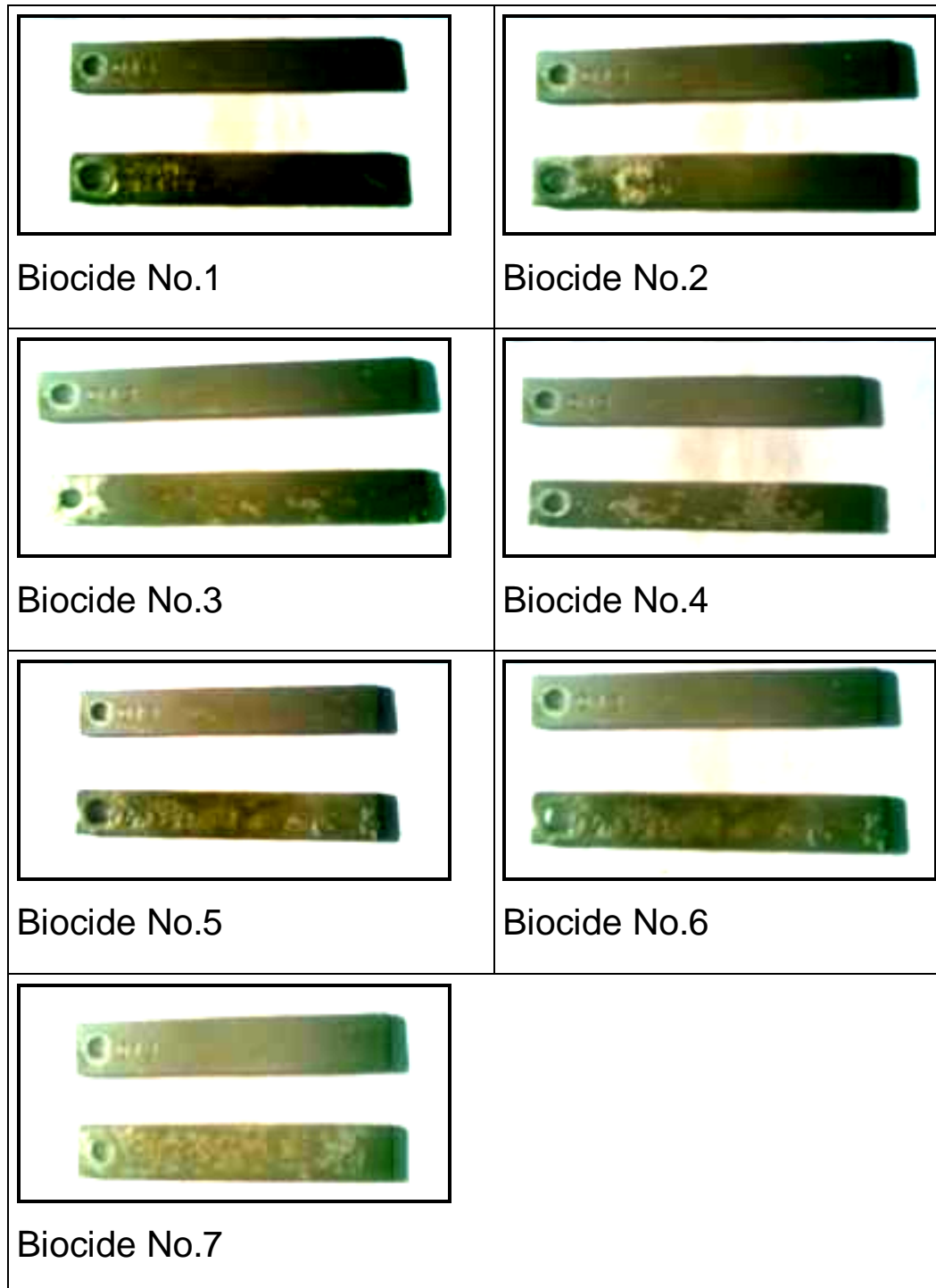


Figure 8. The corroded coupons in the path of water pipes with different biocide.

Polarization test

The polarization curves of steel in water samples without and also containing various biocides are illustrated in Figure 10 (a to h). The amount of biocide value added to

raw water was 10 mg/L. The reference electrode in these experiments was saturated calomel electrode (SCE).

In a polarization curve, whenever the potential is more negative and the current is more positive, the environment is more corrosive. The polarization curves of steel

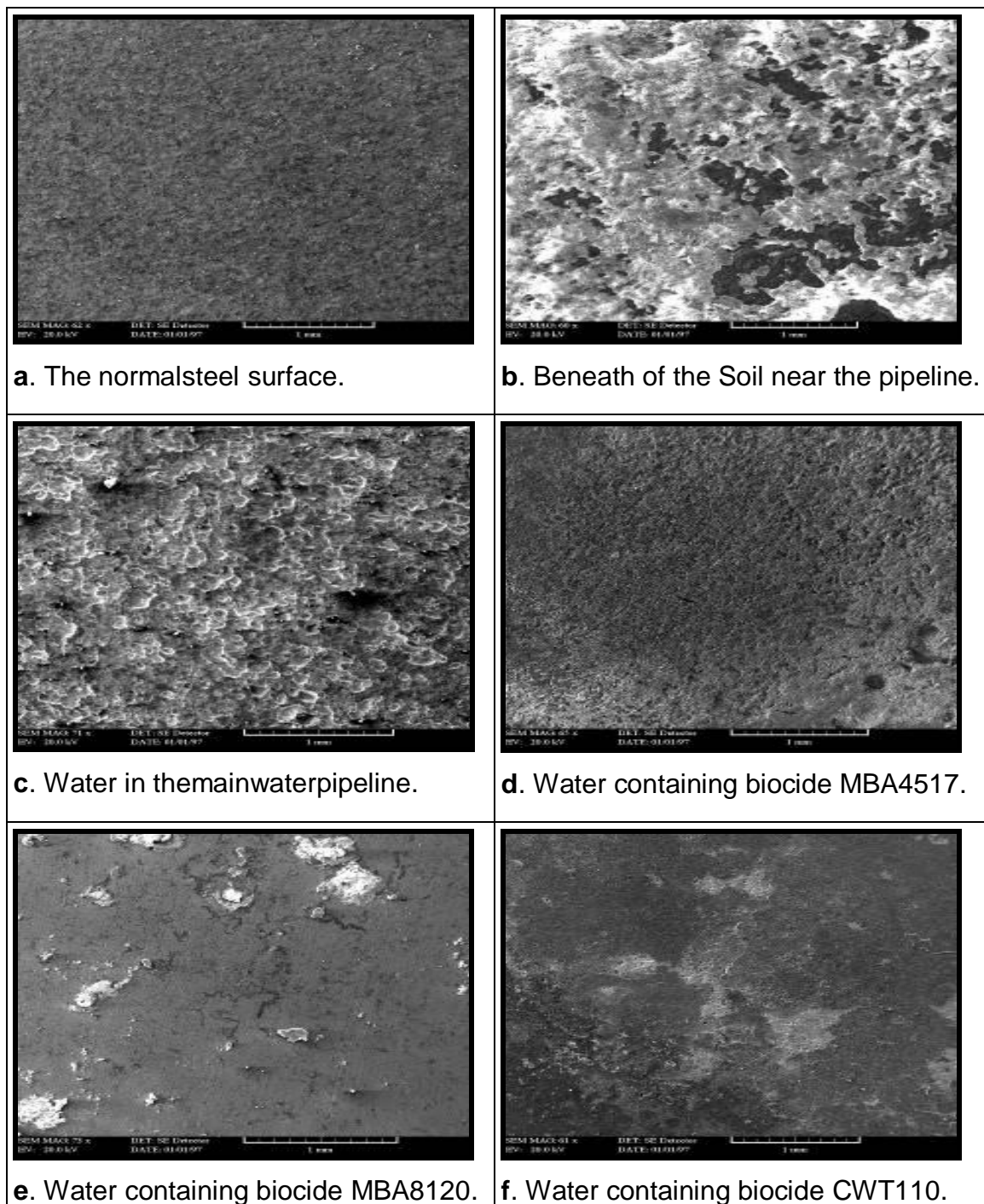


Figure 9. SEM image from the surface of carbon bearing steel coupon.

steel in Figure 10 (a to h), show raw water produced a more negative potential and more positive current than water that contained biocides. The numerical values of parameters obtained from the polarization curves in different situations are given in Table 10. As can be seen, for biocide CWT110, I_{corr} (corrosion current) is minimum and E_{corr} (the potential) is maximum. These results are

consistent with results of corrosion rate determinations and SEM observations indicating this biocide can be used to prevent biocorrosion. Raw water is more corrosive with $9.765 \mu A$ and -690 mV for I_{corr} and E_{corr} , respectively. Also, the anodic and cathodic slopes of the polarization curve are shown by β_a and β_c symbols respectively.

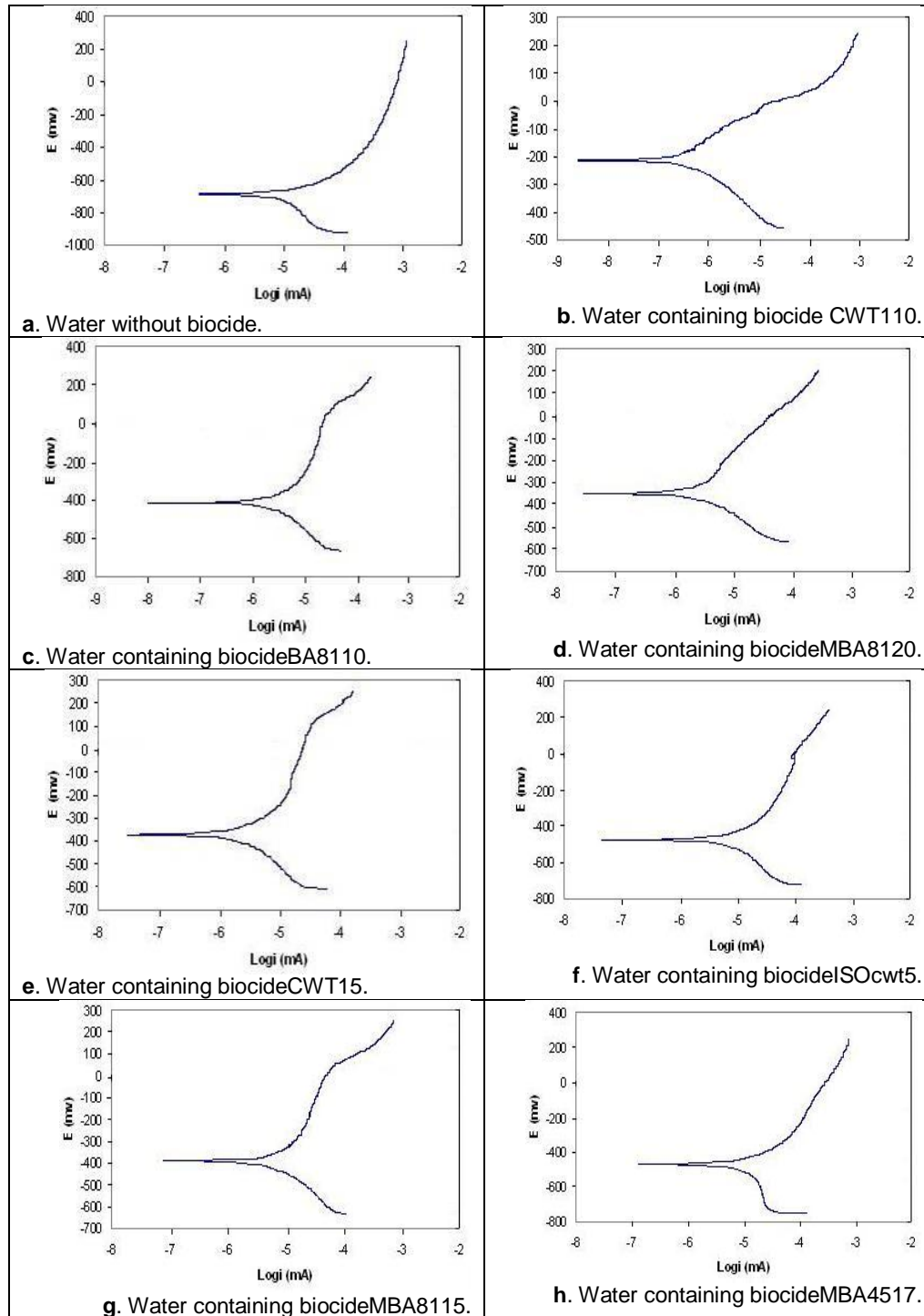


Figure 10. Polarization curve of steel in water samples without and with various biocides.

Conclusion

High amounts of sulphur and the presence of FeS and P in corrosion products indicate that microbial corrosion by SRB occurred in water pipelines at Sarcheshmeh mine. Also, according to the metallographic observations of the

sample and presence of cavities, microbial corrosion of water pipes was confirmed. In addition, the total bacteria count (TBC) and SRB tests in the water samples from 16 wells showed that water in wells No.6 and 16 have the highest amount of SRB bacteria. In view of the presence of SRB in the surrounding soil of water pipeline, cathodic

Table 10. Results of polarization test for raw water and water containing different biocides.

| Biocide | I_{corr} (μA) | E_{corr} (mV) | β_a | β_c |
|-----------|------------------------|-----------------|------------------------|------------------------|
| CWT110 | 1.823 | -213.2 | 219×10^{-3} | 131×10^{-3} |
| MBA8110 | 2.231 | -393.8 | 619.8×10^{-3} | 469×10^{-3} |
| MBA8120 | 3.292 | -358.4 | 561.8×10^{-3} | 219.3×10^{-3} |
| CWT15 | 3.312 | -371.5 | 536.1×10^{-3} | 456.6×10^{-3} |
| ISOcwt5 | 4.124 | -473.8 | 797.7×10^{-3} | 1.001 |
| MBA8115 | 4.672 | -390.6 | 4.649 | 635.1×10^{-3} |
| MBA4517 | 5.392 | -479.5 | 426.8×10^{-3} | 2.67×10^3 |
| Raw water | 9.765 | -690 | 305.3×10^{-3} | 9.987×10^{-3} |

protection potential applied to the pipeline (-0.85 V) cannot appreciably protect from pipeline against corrosion by SRB. Results of the Corratel device and coupons setting showed that corrosion potential in soil surrounding of the water pipeline was higher than raw water. Results of corrosion tests, SEM observations and polarization studies with steel coupons immersed in water in the pipeline at Sarcheshmeh mine showed biocide CWT110 to be most effective in reducing biocorrosion. The use of this biocide in pipeline water at the mine has promise for preventing pipe biocorrosion.

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