

## MINI-REVIEW

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## Role of microorganisms in corrosion inhibition of metals in aquatic habitats

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**Abstract** Bacterial activity at metal surfaces may result in corrosion induction or corrosion inhibition. An important effect of chemoorganotrophic bacteria under aerobic conditions is the removal of oxygen from the metal surface. This is most effectively done by biofilm-forming microorganisms and causes corrosion inhibition. Anaerobes promote corrosion if they consume molecular hydrogen, for example sulfate-reducing bacteria and certain Fe(III)-reducing organisms such as *Shewanella putrefaciens*. Chemoorganotrophic Fe(III) reducers are of special interest because they remove corrosion products and hence destroy ecological niches for sulfate-reducing bacteria beneath the deposits. Also, these chemoorganotrophic bacteria may cause passivation of the metal surface through the consumption of dissolved oxygen, lowering the open circuit potential and the creation of a protective layer of atomic hydrogen on the metal surface.

### Introduction

Deterioration of our environment has necessitated the urgent development of ecologically safe technologies in many industries. This is also true for water systems and, in particular, for corrosion prevention under such conditions. Corrosion processes involve biotic and abiotic factors. The corrosion of metals in cooling water systems, for example, is affected by oxygen concentration

and may be entirely abiotic. Biocorrosion processes on metal surfaces depend on the physiology of the microbial community developing under the influence of the chemical and physical parameters of the environment. In this review we will primarily focus on the impact of bacteria on cathodic corrosion processes.

The methods currently available for the microbial control of water systems are based on the application of biocides (Dhaliwal et al. 1992; Ibars et al. 1992), which in most cases are highly toxic. Their effectiveness gradually decreases due to microbial adaptation and reaction with other components of the aquatic habitat. This has led to the use of chemicals in higher concentrations and results in a disturbance of the ecological balance of the water and surrounding air. The working principle of biocides is based either on suppressing the growth and activity of bacteria from certain taxonomic groups or on the complete extermination of all microorganisms (Dhaliwal et al. 1992; Zhou and King 1995). A negative consequence of exterminating all bacteria is the removal also of those which have been reported to decrease the rate of metal corrosion (Brisou et al. 1973; Basova et al. 1979; Potekhina 1984, 1985a, b, 1996; Pedersen and Hermansson 1989, 1991; Jayaraman et al. 1997a, b, 1998). Biocides are often of limited effectiveness, because biofilms coating the surface of pipes and other materials are not effectively penetrated by these agents. Bacteria, including sulfate-reducing bacteria (SRB), are therefore difficult to control within biofilms (Okabe et al. 1994). Nutrient removal strategies may possibly control SRB growth and activity. It has been shown, however, that the production of extracellular polymeric substances (EPS) by *Desulfovibrio desulfuricans* increased with phosphorus and nitrogen limitation (Okabe and Charaklis 1992; Okabe et al. 1992). As a result, cell production decreased by about 50% but the biofilm was preserved.

Concepts for the protection of metals in industrial water systems are now being developed (Potekhina 1985b, 1990, 1996). Their basis takes advantage of the biological potential of ecosystems. Microorganisms

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which remove corrosion products and dissolved oxygen from the metal surface are the crucial factor in these concepts. In this respect ferric iron [Fe(III)] reduction by certain strains of chemoorganotrophic Fe(III)-reducing bacteria deserves attention. It has been shown that these microorganisms do not initiate any corrosion on mild steel (Potekhina 1985b).

### Effect of chemoorganotrophic bacteria on corrosion processes

According to Hamilton (1985) and Gibson (1990), chemoorganotrophic bacteria can be considered as the forerunners of corrosion-active SRB. They remove oxygen and provide substrates such as organic acids and  $H_2$ ; they also reduce the oxidation–reduction potential in habitats and thus facilitate the growth of SRB.

In the absence of considerable sulfate reduction or with pure cultures of chemoorganotrophs, the effect of chemoorganotrophically growing bacteria may be different; they may induce or inhibit corrosion. It seems that the ability to form a biofilm at the metal surface is very beneficial for corrosion inhibition (Jayaraman et al. 1997a, b). *Streptomyces lividans* does not generate a biofilm and does not promote any corrosion inhibition, whereas biofilm-producing *Pseudomonas fragi* and *Escherichia coli* DH5 $\alpha$  are able to do so. It has been shown that the biofilm must be alive – in other words, the cells must be respiring – otherwise corrosion proceeds, as in the absence of biofilm (Hernandez et al. 1994; Jayaraman et al. 1997a, b). Corrosion of metal coupons also occurred when the cells were removed from suspensions still containing EPS (Pedersen and Hermansson 1991). The authors concluded that the microbial cells must be present, although not attached to the surface. The protective effect even remained when the metal coupons were separated from the cells by a dialysis membrane, indicating that the factor affecting the metal can diffuse through the membrane. This is true for oxygen; the respiring cells would lower its concentration inside as well as outside the membrane. Thus, oxygen must be prevented from diffusing to the metal surface. It is not known whether the microbial biofilm exerts any additional positive effects.

In a study conducted with batch cultures of 42 strains of chemoorganotrophic bacteria isolated from biofilms and water from an industrial cooling system, it was demonstrated that corrosion on metals tends to decrease in the presence of most of these bacterial strains (Basova et al. 1979; Potekhina 1984, 1985b). Using various growth media inoculated with bacteria, a decrease in mass loss of metal was observed, as compared to aerobic sterile controls. The extent of inhibition of metal corrosion was directly related to the amount of cells in the medium and coincided with the level of bacterial activity decreasing the oxygen concentration in the media (Potekhina 1985b). Chemolithotrophic bacteria are also oxygen-consuming, but

they produce aggressive compounds such as sulfuric and nitric acids so that oxygen consumption is associated and over-compensated by chemical corrosion (Iverson 1987; Lopez et al. 1994).

Electrochemical methods have been used to follow the corrosion process (Potekhina 1984). The cathodic curve obtained on mild steel in sterile water from the industrial cooling systems (control) has a typical form for the corrosion process, with intense depolarization on reaction with oxygen. It means that the speed of corrosion in the examined case was determined by the high concentration of oxygen in the media.

The  $E_{oc}$  (open circuit potential) is defined as the potential between the metal coupon (working electrode) and the platinum counter electrode relative to the reference saturated calomel electrode (SCE). Measurements of  $E_{oc}$  changing with time are important for estimating the effect of depolarizers and inhibitors on corrosion reactions. An increase of  $E_{oc}$  means depolarization of the cathode and corrosion. A drop in potential is evidence for decreased corrosion (Romanov 1965).

The  $E_{oc}$  value of mild steel in aerobic media (sterile cooling water) was  $-340$  mV (SCE as reference electrode), moving to  $-240$  mV after 1 h incubation. In media inoculated with chemoorganotrophic bacteria, the open circuit potential decreased to  $-500$  mV after 1 h and to  $-550$  mV after 1 day of exposition (Potekhina 1985b). According to Romanov (1965) such a movement of the  $E_{oc}$  to low values essentially slows the process of dissolving the metal.

In our experiments (Potekhina 1985b) the above-mentioned bacterial strains were applied to an industrial water cooling system with heat-exchanging equipment (Fig. 1). This system, used for cooling oil which has an average temperature of  $75$  °C, consists of two parts. The first is a large water tower with inflowing heated water. This water is cooled by bubbling with cold air and therefore becomes high in oxygen concentration. The second part consists of the pipes and tubes of the heat-exchanging equipment. The circulating cooling water in the system is regularly exchanged for natural river water, because of increasing salt concentrations. The heat-

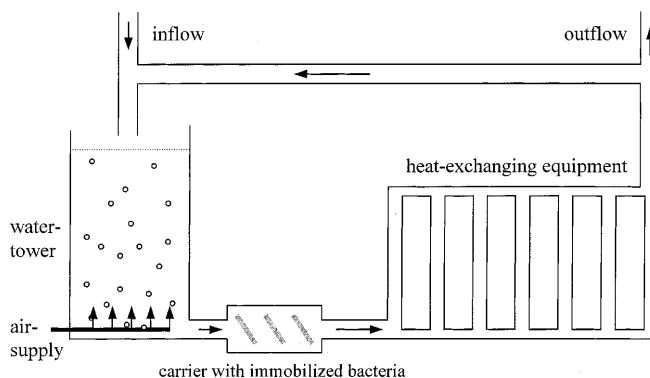


Fig. 1 Scheme of an industrial water cooling system with immobilized bacteria for corrosion inhibition

exchanging equipment was subject to strong corrosion, caused initially by the high oxygen concentration and later by the action of SRB which colonized the deposits under the aerobic biofilm. To avoid these problems, corrosion-inhibiting bacteria were immobilized on solid carriers and placed in the water tower at the entrance to the second part of the system. As the result, the amount of dissolved oxygen, carbon sources, phosphorus, nitrogen and other elements in the water flowing through the heat-exchanging equipment were reduced by the immobilized bacteria. Such water, low in nutrients and oxygen, impaired the formation of a biofilm in the second part of the system. An important consequence of immobilizing the bacteria was the resulting spatial separation of microbial processes between the zone of aeration (first part) and the heat-exchanging equipment (second part). At the same time, oxygen limitation led to a decreased formation of corrosion products on the metal surface. Thus, the corrosion process may be controlled by an enforced oxygen and nutrient consumption in a unit favouring biofilm formation.

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### **SRB and induction of corrosion by cathodic depolarization of metals**

SRB – a physiological group of microorganisms – are very versatile with respect to the number of substrates utilized. They are well adapted to various anaerobic ecological niches (Widdel 1988; Ford and Mitchell 1989) and are an active component in sulfate-containing ecosystems (Jørgensen 1983). The role of SRB in anaerobic corrosion processes is indisputable (Hamilton 1985; Tomei and Mitchell 1986; Little et al. 1991; Angell et al. 1995; Chen et al. 1995). The process of corrosion is directly linked to the growth and activity of these bacteria.

More than 60 years ago, Von Wolzogen Kühr and Van der Vlugt (1934) suggested that metal corrosion could result from the sulfate reducer's metabolic oxidation of molecular hydrogen on the cathodic side of the metal. The validity of their suggestion was proven later by applying polarization and potentiostatic methods to the investigation of steel and aluminium corrosion with cultures of SRB. It was possible to detect a cathodic depolarization under the impact of these bacteria (Booth and Tiller 1960, 1967; Iverson 1966). The effect of hydrogen removal from the metal surface and ferrous sulfide (FeS) formation in SRB-induced corrosion was recently stressed by Little and Wagner (1997). The contribution of FeS to the cathodic depolarization was investigated by Tiller and Booth (1962). Chemically pure FeS was incorporated into a sulfate-free nutrient medium containing fumarate and *D. desulfuricans*. The rate of corrosion was proportional to the amount of FeS added and depended on the contact of FeS with metal surfaces. These results allowed a reinterpretation of the way metal corrosion is induced by sulfate reducers. The build-up of FeS in the medium and its deposition on metal surfaces gives rise to the formation of an electro-

chemical cell with iron as the anode and FeS as the cathode.

King and Miller (1971), King and Wakerley (1973), Smith and Miller (1975) and McNeil and Little (1990) support the hydrogenase theory. They propose that cathodic depolarization occurs on the iron sulfide instead of the unreachable iron surface. However, the activity of FeS, as the cathode, decreases after some time because of the binding of atomic hydrogen. The removal of molecular hydrogen and, hence, the reestablishment of the cathodic function of FeS is affected by bacterial hydrogenases.

Hardy (1983) found a direct relationship between the oxidation of cathodic hydrogen by *Desulfovibrio* species and the depolarization of samples of mild steel. He noticed some instability of the depolarization process, since FeS lowers the rate of converting atomic to molecular hydrogen, which is used as a substrate for the bacterial hydrogenase. Ferris et al. (1992) proposed that electrons are channelled from metal to bacteria by the FeS matrix within corrosion deposits on the surface of metals.

The importance of oxygen on the SRB-related corrosion of ferrous metals and alloys has been emphasized by several authors. Acceleration of corrosion rates was observed when iron, corroded in the presence of SRB, was exposed to intermittent aerobic/anaerobic conditions (Starkey 1986). Hardy and Bown (1984) obtained data supporting the influence of oxygen on the corrosion induced by *Desulfovibrio* sp. The sequential exposure of the samples to fresh air resulted in an almost 100-fold increase in the corrosion rate as compared to the corrosion observed in media inoculated with bacteria before aeration. The formation of nodules, was noticed on the metal surface under a layer of black adhesive film during anaerobic growth of bacteria. The reaeration gave rise to a pitting effect under these nodules, which was associated with oxidation of the metal and the formation of thiosulfate.

As clearly demonstrated by Lee et al. (1993a), SRB activity at the substratum beneath a biofilm can be extensive, even at high dissolved oxygen concentrations in the bulk water. Furthermore, introducing oxygen into some industrial water systems increases the extent of pitting corrosion due to the formation of corrosion components such as elemental sulfur and/or pyrite. SRB biofilm development on steel surfaces and its subsequent influence on corrosion have been reported both in totally anaerobic systems and under the influence of low and high oxygen concentrations (Lee et al. 1993a, b, 1994). Corrosion occurred after the SRB had developed and a significant amount of FeS had contacted the metal. Lee and Characklis (1993) concluded from laboratory studies that there is no direct correlation between corrosion of carbon steel and SRB activity. But the nature and extent of corrosion was closely related to the physical form of FeS. Crolet et al. (1993) showed that SRB growing with organic substrates and producing weak acids such as acetate may affect the pH of their environment. Precipitation of FeS and thiosulfate formation

with traces of oxygen may induce corrosion more effectively than hydrogen consumption. Pitting corrosion at the metal surface is favoured by galvanic coupling between the acidified anode and the pH-stabilized cathode. This theory is consistent with the results of Guezennec et al. (1994). Campaignolle (1993) reported the need for SRB to be present on both the anode and the cathode to stabilize the localized corrosion of carbon steel. It has been shown by Dilling and Cypionka (1990) that SRB are able to consume oxygen, and hydrogen can be consumed at very high rates by oxygen respiration (Fitz and Cypionka 1991). This implicates two possible mechanisms for hydrogen removal by SRB in alternative oxic/anoxic systems via sulfate reduction or aerobic respiration (Nielsen et al. 1993).

Thus, numerous experiments are now available demonstrating that SRB cause corrosion (Widdel 1988; Voordouw et al. 1990; Geiger et al. 1993; Magot et al. 1995). But only the sum of the various effects of interaction between the three components (microorganisms, metal, solutes) can explain the whole process of biocorrosion. Under strictly anaerobic conditions with nutrient limitation, bacterial hydrogenase activity is the primary reason for the degradation by removing hydrogen and depolarizing the cathode (Videla 1996). With organic substrates present and in oxic/anoxic systems, other parameters predominate.

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### **Fe(III)-reducing bacteria and their role in corrosion inhibition**

It has been established that anaerobic zones in industrial water systems and anaerobic ecosystems in nature are colonized by sulfate-reducing, denitrifying, Fe(III)- and Mn(IV)-reducing, methanogenic and fermentative microorganisms (Stewart and Jonston 1982). In the microbial communities of such ecosystems, molecular hydrogen and acetate were found to be the major substrates, not only for SRB, but also for methanogenic (Daniels et al. 1984) and Fe(III)-reducing bacteria (Lovley 1993).

Dissimilatory Fe(III) reduction has been found to compete successfully for these substrates not only with methanogenesis, but also with sulfate reduction. Lovley and Phillips (1987) studied the mechanism of inhibition of methanogenesis and sulfidogenesis by Fe(III). They found that the residual level of molecular hydrogen and acetate in natural environments with Fe(III)-reduction is much lower than in deposits with predominantly methanogenesis or sulfate reduction. Thus, Fe(III)-reducing bacteria have a higher affinity for molecular hydrogen and acetate, reflecting the fact that the change in free energy of the energy-conserving redox reaction is larger than in sulfate reducers or methanogens (Lovley et al. 1994).

The incorporation of Fe(III) into natural deposits with predominantly methanogenesis or sulfidogenesis resulted in 95% inhibition of these processes, with no

toxic impact of Fe(III) compounds on sulfate-reducing and methane-generating microorganisms. Even after a 3-week incubation with Fe(III) and additional hydrogen, the reduction of sulfate and the generation of methane recovered again. Thus, the competition for electron donors among the microorganisms responsible for Fe(III) reduction, sulfidogenesis and methanogenesis seems to be the principal factor controlling the distribution of the three major reactions in anaerobic environments. However, the rate of bacterial metabolism of organic substances in sediments is limited by the rate of electron transfer from donor to acceptor. Fe(III)-reducing bacteria redistribute the electron flux from sulfate reduction to Fe(III) reduction if Fe(III) compounds are present in an accessible form in the medium (Lovley and Phillips 1987; Chapelle et al. 1995). Less crystallized forms have been reduced more easily. The magnitude of reduction for different Fe(III) compounds was determined by Ottow (1969), who found the following sequence of decreasing suitability: ferric phosphate, ferric hydroxide, ferric oxyhydroxide, ferric oxide. The dependence of Fe(III) reduction upon the extent of crystallization was explained by the fact that less crystallized forms of Fe(III) are more soluble and have a larger surface (Munch and Ottow 1980; Heron et al. 1994).

Based on their physiology, Fe(III)-reducing bacteria can be divided into two groups.

1. Dissimilatory Fe(III)-reducing bacteria: Most of the electron transfer to Fe(III) found in sedimentary environments results from the oxidation of fermentation products. Acetate and molecular hydrogen are considered the most important substrates. The first dissimilatory iron-reducing bacteria were isolated by Balashova and Zavarzin (1980) and Obuekwe et al. (1981a, b), being described as *Pseudomonas* spp. and later classified as *Shewanella putrefaciens* (MacDonell and Colwell 1985; Nealson and Saffarini 1994). These organisms possess hydrogenase, utilize molecular hydrogen for Fe(III) reduction and induce corrosion (Obuekwe et al. 1981a, b, 1983). Another example for a well-studied iron reducer is the strictly anaerobic *Geobacter metallireducens*, which couples the oxidation of acetate to carbon dioxide with the reduction of Fe(III) (Lovley et al. 1993). Recently, a wide range of phylogenetically diverse dissimilatory iron reducers has been isolated (Lovley 1997).

2. Chemoorganotrophic Fe(III)-reducing bacteria: Many microorganisms (*Bacillus* and *Vibrio* spp.) are known to transfer minor portions of electrons to Fe(III) during glucose fermentation. Lovley (1993) indicated that, in all cases examined, Fe(III) reduction is a side reaction and none of these organisms has been found to grow as a result of this process. Ehrlich (1995), however, pointed out that the inability of such systems to couple Fe(III) reduction with energy conservation has not been demonstrated. Roberts (1947) showed in experiments with *Bacillus polymyxa* grown anaerobically on glucose in the presence or absence of Fe(III) that approximately twice as much glucose was consumed in cases where

Fe(III)-reduction occurred. Comparable results were obtained by Bromfield (1954).

Our experimental data showed that axenic cultures of chemoorganotrophic Fe(III)-reducing bacteria grown anaerobically on glucose can use Fe(III)-containing corrosion products from metal surfaces as terminal electron acceptors (Potekhina 1985b). We had selected six strains of chemoorganotrophic bacteria for further investigations which belong to the genera *Pseudomonas*, *Micrococcus*, *Arthrobacter* and *Vibrio*.

Metal plates covered with corrosion products were removed after 8-week exposure to cooling water and placed in vessels containing a glucose–mineral, bacteria-inoculated medium. The subsequent exfoliation of corrosion products from the metal surface from 10% to 57% (depending on the strain) was accompanied by a darkening of the plates and the culture medium. The efficiency of corrosion product removal by *Pseudomonas* sp. 2 was enhanced by increasing the concentration of glucose in the medium and was followed by a decrease in pH and the formation of CO<sub>2</sub> bubbles. We achieved removal of 80–90% of the ferric corrosion products and their conversion into soluble Fe(III) compounds, as confirmed by chemical analyses. No exfoliation was observed in a bacteria-free medium; a slight decrease in plate mass was recorded for the chemical control, which can only be explained by the continued corrosion of plates in bacteria-free medium. The addition of up to 10% sterile glucose into the bacteria-free medium did not affect the exfoliation of corrosion deposits. These results can be interpreted such that if oxygen is limiting or lacking in the medium, chemoorganotrophic bacteria are capable of using corrosion products in the form of Fe(III) compounds as terminal electron acceptors. These results ensure the development of methods for the removal of corrosion products from metal surfaces by selected bacterial strains (Potekhina et al. 1985; Potekhina 1996). An additional positive finding was that no trace of corrosion was observed on plates placed in a bacteria-containing medium for a prolonged exposure.

Also, a drop in  $E_{oc}$  value was found, to levels much lower than those in controls and those under aerobic conditions (Potekhina 1985b). Jayaraman et al. (1997a) have shown a decrease in corrosion with *Escherichia coli* DH5 $\alpha$ , and *Pseudomonas fragi* grown aerobically or anaerobically, as compared with sterile medium. A decrease of  $E_{oc}$  in anaerobic cultures of *E. coli* was also observed, as compared with controls. These studies of potential changes in bacterial cultures indicate that  $E_{oc}$  decreases under anaerobic conditions to more negative values than in aerobic media with bacteria. Bacteria were found to react with ferric compounds, but they remained indifferent to the chemical coating which protects metal surfaces.

The introduction of these chemoorganotrophic bacteria to non-sterile industrial water systems, which contain sulfate-reducing and other corrosion-inducing bacteria, caused not only the exfoliation of corrosion products but also the protection of the metal surfaces

from further corrosion. An important consequence of corrosion product removal by chemoorganotrophic Fe(III)-reducing bacteria is the destruction of ecological niches for sulfate-reducers which were normally found under the deposit on metal surfaces.

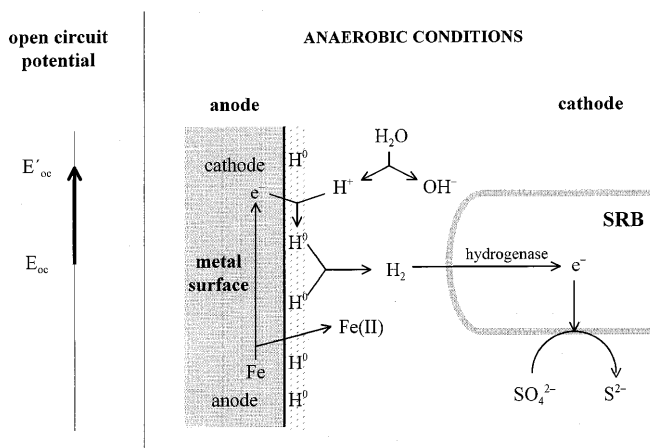
## Conclusion

Analysis of the experimental data obtained so far reveals two contrasting types of bacteria in respect to their effect on metals. Corrosion increases in the presence of bacteria type I and decreases with bacteria type II.

Hydrogen-consuming bacteria, such as SRB (Odom and Peck 1984; Hamilton 1985; Magot et al. 1995), *Shewanella putrefaciens* (Obuekwe et al. 1981a, b, 1983), certain nitrate-reducing bacteria (Mara and Williams 1971a) and phototrophic bacteria (Mara and Williams 1971b, 1972) belong to type I. The results of electrochemical studies showed that  $E_{oc}$  moves to more positive values and cathodic curves shift to an area of larger currents under the influence of such bacteria. This coincides with the depolarization of the cathode and enhancement of mass loss of mild steel coupons.

It may be concluded that under anaerobic conditions an additional galvanic pair is established between corrosion-inducing bacteria and the metal surface, in which bacterial cells act as cathode and the metal as a whole acts as anode, because electrons flow from metal to bacteria (Fig. 2). It was mentioned that SRB consume electrons from the surface of metal, thereby accomplishing the depolarization of the cathode at the metal surface. The open circuit potential at the metal surface increases and moves to more positive values. This process continues as long as the bacteria are active.

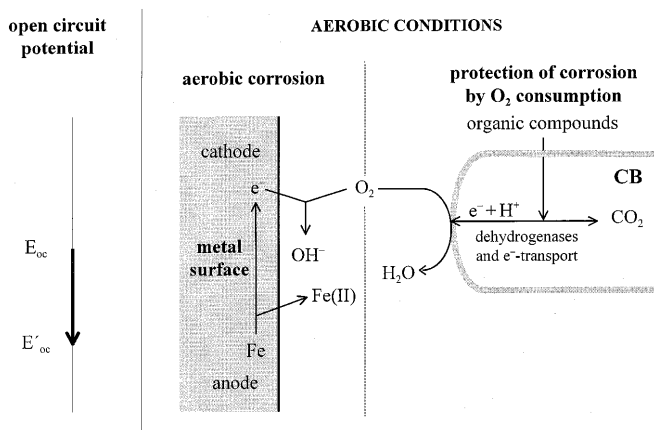
Bacteria which generate reducing power but do not possess hydrogenase belong to type II. This group protects metals from corrosion under aerobic (Brisou et al.



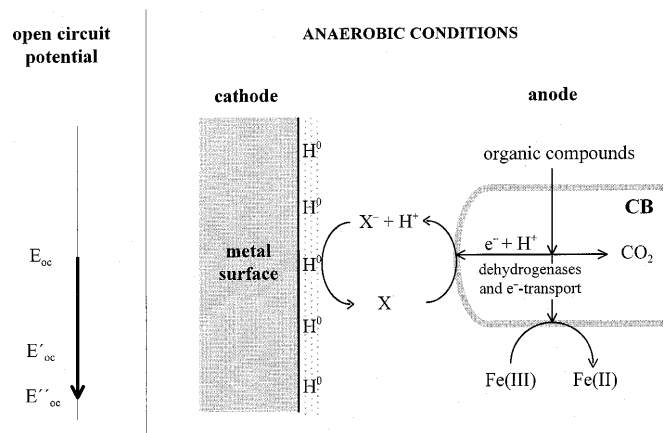
**Fig. 2** Role of hydrogen-consuming sulfate-reducing bacteria (SRB) in anaerobic corrosion.  $E_{oc}$  Open circuit potential in anaerobic media without bacteria,  $E'_{oc}$  open circuit potential in anaerobic media with bacteria

1973; Potekhina 1984; Pedersen and Hermansson 1991) as well as under anaerobic conditions (Potekhina 1985b; Jayaraman et al. 1997b). The reducing power generated by substrate breakdown is fed into the respiratory chain, resulting in the consumption of molecular oxygen (Fig. 3). The removal of oxygen leads to a drop in the cathodic reactions at the metal surface and a slowing of the metal dissolution. This in turn is followed by an accumulation of electrons released by anodic reactions in the metal itself. The drop in  $E_{oc}$  values coincides with decreasing  $O_2$  concentration in the media with bacteria. Afterwards, the  $E_{oc}$  stabilizes as a result of decreasing electron flow. The mass loss in media inoculated with bacteria as compared to sterile controls is significantly lower (12–96% less mass loss than in control, depending on strain). The composition of media for chemoorganotrophic bacteria (organic compounds present, buffer system etc.) does not seem to be the crucial factor for the change of  $E_{oc}$ , cathodic reactions and mass loss of metal. In contrast, the amount of bacteria added and the growth phase of the bacteria strongly affects this process (Potekhina 1985b).

Under anaerobic conditions, the mechanism of corrosion protection is likely to be connected with the transmission of electrons and protons from bacterial cells to the metal surface. This leads to the formation of a  $H^0$  layer at the metal surface as depicted in Fig. 4. In contrast to SRB and other bacteria belonging to type I, these bacteria act as anode and the metal as cathode in the galvanic pair between bacteria and metal. This resembles a known method of cathodic protection against corrosion, in which a galvanic pair between mild steel (cathode) and zinc (anode) is established. Under such conditions SRB develop very slowly during a long period of incubation (Kasahara et al. 1995). It may be this is a way to discharge the cells and to achieve very positive values of the redox potential on the cells. However, the mechanism of electron transfer is not clear. Probably, some redox-active compounds released to the media



**Fig. 3** Scheme of aerobic corrosion of metals and the proposed role of chemoorganotrophic bacteria (*CB*) in corrosion inhibition.  $E_{oc}$  Open circuit potential in aerobic media without bacteria,  $E'_{oc}$  open circuit potential in aerobic media with bacteria



**Fig. 4** Proposed mechanism of anaerobic protection of metals by chemoorganotrophic Fe(III)-reducing bacteria (*CB*).  $E_{oc}$  Open circuit potential in anaerobic media without bacteria,  $E'_{oc}$  open circuit potential in aerobic media with bacteria,  $E''_{oc}$  open circuit potential in anaerobic media with bacteria,  $X$  unknown electron mediator

from dead cells or extracellular cytochromes (Seeliger et al. 1998) could be responsible for electron transfer from bacterial cells to the metal. Recently, Hyun et al. (1998) also noticed some kind of electron transfer from lactate-grown *Shewanella putrefaciens* cells to the electrode by unidentified carriers. The further advantage of the chemoorganotrophic Fe(III)-reducing bacteria is the removal of corrosion deposits from the metal surface by reducing them to soluble Fe(II). The use of immobilized bacteria and their introduction into industrial water systems could be acceptable. First, because they decrease the oxygen-dependent corrosion processes; also, their activity may limit the nutrient supply for SRB.

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