Research Article

Journal of Oil and Gas Research Reviews

A Review of Biological attack on Concrete and Steel to Assess its its Possible Impact On Mechanical Deterioration of Gravity Based Structure (CGBS) off-shore Platforms

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Submitted: 13 Sep 2022; **Accepted**: 19 Sep 2022; **Published**: 27 Sep 2022

Citation: *Reza Javaherdashti,. (2022). A Review of Biological attack on Concrete and Steel to Assess its its Possible Impact On Mechanical Deterioration of Gravity Based Structure (CGBS) off-shore Platforms. Journal of Oil and Gas Research Reviews, 2(1), 01-12.*

Abstract

When it comes to reinforced concrete (RC) structures, the problem of Microbiologically Influenced Corrosion (MIC) of steel and Microbiologically Influenced Deterioration (MID) of concrete can have a joint disastrous effect on the integrity of the structure. MIC of steel (and other metals) has been the subject of many researches for many years, so have been the MID problems in sewage systems and wastewater treatment facilities. However, there are very few published materials to address MIC/MID scenarios in concrete gravity based (CGBS) platforms. This paper reviews some of the possible mechanisms that can be involved in MIC/MID events in such structures along with evaluating the feasibility of current countermeasures taken in practice.

Key Words: Corrosion-Microbiologically Influenced Corrosion (MIC)- Biodterioration-Concrete-Steel- Sulphate Reducing Bacteria (SRB)- Sulphur Oxidising Bacteria (SOB) –Biocide.

Introduction

The topic of this review will be microbiologically influenced corrosion (MIC) of carbon steel and Microbiologically Influenced Deterioration (MID) of concrete. The reason for considering such materials is that they are the main components of reinforced concrete (CR) structures. Therefore, failure of one will, sooner or later, cause the failure of the other. Mechanically, the RC can be taken as a composite material where the mechanical properties of both involved phases, that is, concrete and steel are employed. The relatively low tensile strength of concrete is compensated by high tensile strength of steel and the relatively low corrosion resistance of steel is largely compensated by concrete as the following:

When high-pH concrete is in contact with steel, it will produce a passive film that will prevent corrosion of the steel through establishing electrochemical cells. Therefore, the passivated steel will act as cathode and will be safe- as far as the chemical conditions will allow it sustain its passivity. It will be in this context that the diffusion of corrosive anions such as chlorides in concrete becomes important as existence of such anions can be the main factor in determining the time of initiation phase of concrete corrosion where corrosive agents such as chlorides or carbon dioxide will be reaching the steel-concrete interface to initiate corrosion [1]. The details of chemical contribution of concrete to protect steel has been discussed in length in the literature [2, 3]. An important field of application for RC structures is in off-shore structures such as Concrete Gravity Based Structures (CGBS) platforms. First of these 50 CGBS platforms was installed in 1973 (operated by Philips in North Sea at a depth of 71 m) up to 2008(one operated by MPU Heavy Lifter and one by Exxon Mobil), with minimum and maximum depths of operation being 15 m and 350m [4]. The environment (sweater) in which such structures are operating is a quite dynamic and active environment from a corrosion point of view and specially MIC and MID.

This will add into the complexity of clearly defining the possible corrosion scenario(s) to be expected. Also, as using traditional countermeasures against MIC/MID, such as use of biocides, in off-shore platforms is greatly prohibited due to possible environmental issues it can create, this will add another dimension to the complexity of the kinetics of MIC/MID.

Relatively thick concrete cover of reinforcement steel inside concrete may give the impression that the structure could long for a very long periods of time. However, there could exist a range of uncertainties in both design and operation of such structures due to factors as the followings:

- ❖ Due to localised nature of MIC/MID, corrosion may take place much faster than expected. Therefore, uniform corrosion rates normally used in assessing the vulnerability of the structure to corrosion must not be over-trusted,

- ❖ The complexity involved in characterizing the corrosivity of the seawater from a microbiological point of view: for example, the actual number and species that may be involved in causing problems, in the case of organisms capable of macro-fouling, at least 4000 different species of organisms have been recorded as "marine fouling nuisances" the most important of which are, for instance, barnacles, mussels, sponges, coelenterates, bryozoans, serpulids, tunicates, amphipods, algae and marine borers) [5]. However, considering the depths of CGBS platforms, it can be said that while macro-fouling may not be a problem, in the deep oceans, microfouling (bacteria) and biofilm formation-thus affecting corrosion- can be expected [6].

- ❖ Another source of complexity comes from the fuzziness often observed in the interaction between macro-and micro-organisms with each other on one hand and the kinetics involved in letting MIC/MID occur before or after non-microbial corrosion on the other hand.

In this review, we will look at important MIC/MID mechanisms and some of the possible remedies that can be made available. Our main goals in this review will be to draw the attention of the readers to the following points:

1) Complexity involved in MIC/MID specially when coupled with non-microbial electrochemical corrosion,
2) Understanding the underlying MIC/MID mechanisms in order to apply a better design and prevention/mitigation strategies.

Concrete Gravity Based Structures: A brief Review

Concrete Gravity based Structures are a type of Gravity based Structures (GBS). Among many designs available , the main design principle is that fundation of a GBS can consist of mainly a large flat base (to resist overturning loads imposed by the wind and wave), and a conical part at the water surface level (to break the ice and reduce the ice load) [7]. In order to keep the GBS attached to the sea bed, ballasts are used and put on the flat base. In this way, the movement of the foundation will be restricted, thus preventing detachment from the seabed [8].

During the fabrication of fixed GBS structures, they are first made inside an unflooded dry-dock and the equipment are installed and tested. It is after this stage that the floating of the GBS to take it to the installation site is carried out by flooding the dock, to be followed by towing to the terminal site to fix it on the seafloor [9]. Figure 1 shows a schematic, simplified CGBS platform design.

The typical thickness of CGBS platforms are between 0.5-0.8 m with a minimum of 0.4 m and a maximum of 2.0 m. In this regards, not only mechanical integrity of the structure against adverse environmental conditions (such as the action of the waves) can be achieved, it will also grant the structure an increased margin of safety from a corrosion point of view as even very severe corrosion rates–if they happen uniformly-will need a quite long time to be considered as a real threat to the whole integrity of the structure. The main point of concern, however, is that this margin of safety will only be achieved if the corrosion process is assumed of showing a uniform nature. In cases such as MIC/MID, the main feature of the corrosion is its localised form, therefore, decreasing the safety margin considerably.

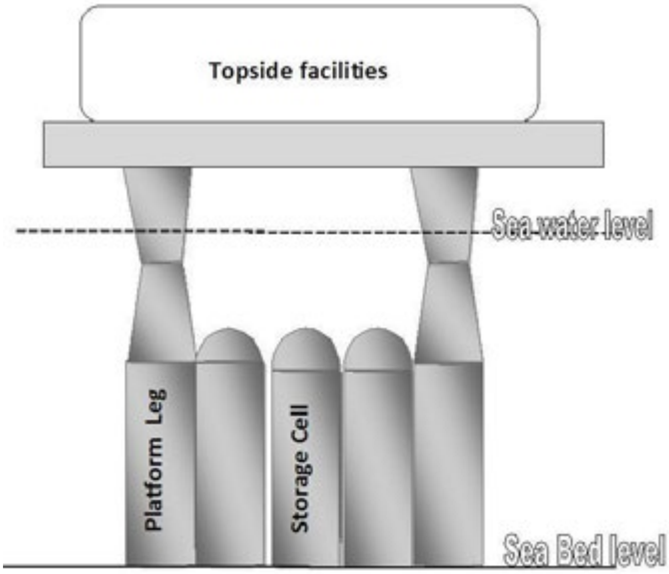


Figure1: Schematic presentation of CGBS platforms with platform leg and storage cells being the main parts of such platforms that are susceptible to MIC/MID). The average depth of operation (between the sea level and the seabed level) for such structures in open seas is about 114 m.

MIC/MID and CGBS platforms

Microbiologically influenced corrosion (MIC) has been defined in many ways in the related literature [10-13]. However, what is common among all these definitions are the following three points [14]:

1. MIC is an electrochemical process,
2. Micro-organisms are capable of affecting both the extent, severity and course of corrosion,
3. In addition to the presence of micro-organisms, an energy source, a carbon source, an electron donator, an electron acceptor and water must be also present to initiate MIC.

Almost all engineering materials are vulnerable to MIC , , including concrete [15-19]. It seems that while materials other than concrete can be deteriorated by the action of more than one type of corrosion-related bacteria (for example, for steels, corrosive impacts of both sulphate reducing bacteria (SRB) and iron reducing bacteria (IRB) are known), there are very few types of bacteria that can actually affect the integrity of concrete, a key player of which being sulphur oxidising bacteria (SOB) [14, 20-22].

As mentioned earlier, while in the deep ocean there is no issue of macrfouling, the bacteria and their ability to form biofilms are still available. The issue of MIC is so serious that DNV standards put it clearly [23]. *"In the submerged and buried zones, corrosion is mostly governed by MIC causing colonies of corrosion pits. Corrosion as uniform attack is unlikely to significantly exceed about 0.1 mm per year but the rate of pitting may be much higher; 1 mm per year and even more under conditions favouring high bacterial activity (e.g. ambient temperature of 20C to 40 C and access to organic material, including crude oil).*

Perhaps one of the earliest reports concerning MIC in a CGBS platform was the short report by T.G. Wilkinson in 1983 where he clearly described the SRB and SOB-related corrosion problems in some parts of the platforms-then operated by Shell in the North Sea [24]. The vulnerable parts of the platform were:

1. Storage tanks (with some 200.000 m3 capacity using water displacement systems)
2. In the legs of the platform (reportedly contained waster up to 20,000 m3)
3. Specific facilities such as the oil/water separators

There have been other MIC-related incidents in other such platform as well. One of such examples has been on the Tank-Doris (operated by Phillips in the North Sea) where it was found out that in the legs of the gravity structures, sulphide generation at the base of the structures and oxygenation at the upper level of water had resulted in the growth of sulphur oxidising bacteria and thus generation of sulphuric acid that would form an obvious threat to concrete.

What are common in all of the cases studied so far, can be summarized as follows:

I. Existence of stagnant untreated seawater
II. Conditions favouring mixing water with oil
III. Existence of materials known to have been vulnerable to MIC/MID,
IV. Cyclic effect of sulphate reducing bacteria (SRB) and sulphur oxidising bacteria (SOB) under oxygen diffusion conditions generated in the susceptible structures

In the next section we will focus more on SRB and SOB and how they are capable of contributing to corrosion.

MIC/MID Mechanisms as induced by SRB and SOB:

The Heart of the issue of MIC is biofilm formation. Biofilm can be defined as a negatively charged, open structure under which localised corrosion can happen. Biofilm is in fact a consortium of different types of bacteria along with non-biological material [14]. Biofilms are highly likely to contribute to corrosion by establishing different oxygen partial pressures, anodic and cathodic sites are produced, resulting in under-biofilm perforation [25].

Of the bacteria that can be present in a biofilm are sulphate reducing bacteria (SRB) and sulphur oxidising bacteria (SOB). Below we will briefly some of the features related to these two types of bacteria. These bacteria and their characteristics have been more extensively reviewed and explained elsewhere [13].

SOB- sulphur oxidising bacteria are capable of producing very acidic sulphuric acid (pH =1) by oxidising either elemental sulphur or hydrogen sulphide. SOB have a relatively long story of enhancing corrosion of steels and concretes [26, 27]. Parker in a series of studies that were published between mid 40s' to early 50s' reported the involvement of SOB in concrete corrosion for the first time. However, it must be mentioned that in early 40s' Lucey Alford as a bacteriologist at the Spotswood Pumping Station, in Melbourne, had identified several groups of bacteria, including Desulfovibrio (a kind of SRB) and Thiobacillus (a kind of SOB), and the symbiotic relationship which involved the breakdown of sulphur compounds in the sewage to hydrogen sulphide [19]. Basically, the corrosive effect of the SOB on concrete structures can be followed after a chemical, non-microbial, corrosion phase has happened. A rather accepted scenario of MID of concrete structures considers that it occurs in three consecutive phases as schematically shown in Figure 2 despite that at the moment, no report actually suggests the time length of each phase.

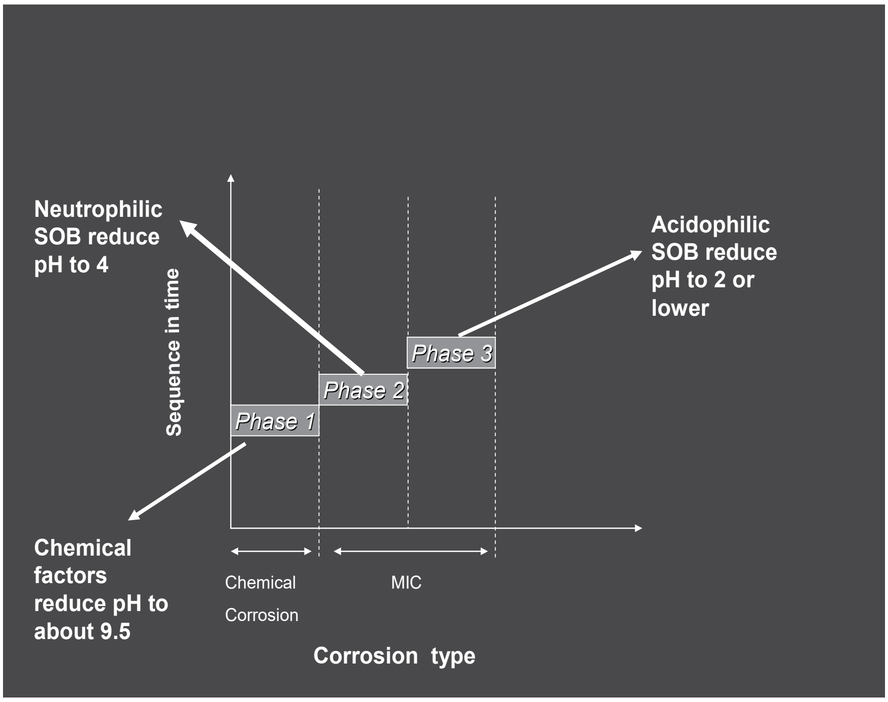


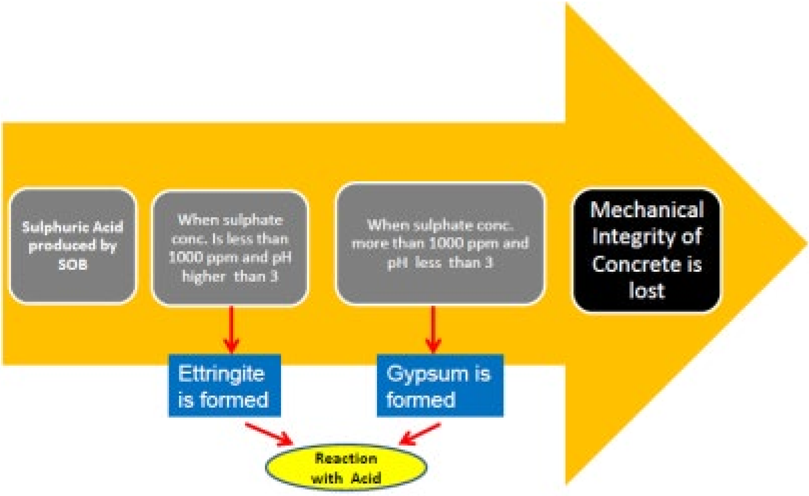
Figure2: Schematic Presentation of Corrosion Phases Involved in MID of Concrete [14].

These three phases of MID are as follows [14]:

- Phase 1: Combined corrosive effects of atmospheric carbon dioxide and hydrogen sulphide reduce pH from >13 to about 9.5.
- Phase 2: First stage of "microbial succession" where, provided that sufficient nutrients, moisture and oxygen exist; some species of sulphur oxidising bacteria (eg., Thiobacillus sp.) can attach themselves onto the concrete surface and grow. Mostly, these species of SOB are neutrophilic sulphur oxidising bacteria (NSOM). These bacteria produce some acidic products and convert the present sulphides to elemental sulphur and polythionic acids.
- Phase 3: Being the second step of the microbial succession, it is normally followed after Phase 2 where the pH has been significantly reduced, another species of SOB known as acidophilic sulphur-oxidising bacteria (ASOM) such as T. thiooxidans colonize the concrete surface and acts to further reduce the acidity.

The chemistry involved in increasing corrosion after sulphuric acid has been produced can be summarized as follows [28]:

The generated sulphuric acid reacts with the lime in the concrete to produce gypsum which is a hydrated calcium sulphate and due to difference in density between the concrete and the corrosion by-products, penetration of the corrosive gypsum layer into the concrete is initiated. Then, gypsum reacts with calcium aluminate of the concrete to yield ettringite ($3CaO\ .\ Al_2O_3\ .\ 3CaSO_4\ .\ 32H_2O$). This product will in turn increase the internal stresses, resulting in the formation of larger and more fresh surface areas (in the form of cracks) to provide enhanced degradation and acid penetration sites. Many studies regarding MID of concrete by ASOM have recorded corrosion rates between 2.7 mm/year to 4.7 mm/year [21]. Figure 3 shows a schematic presentation of acid interaction with concrete and an example of gypsum and ettringite micro-crystals.



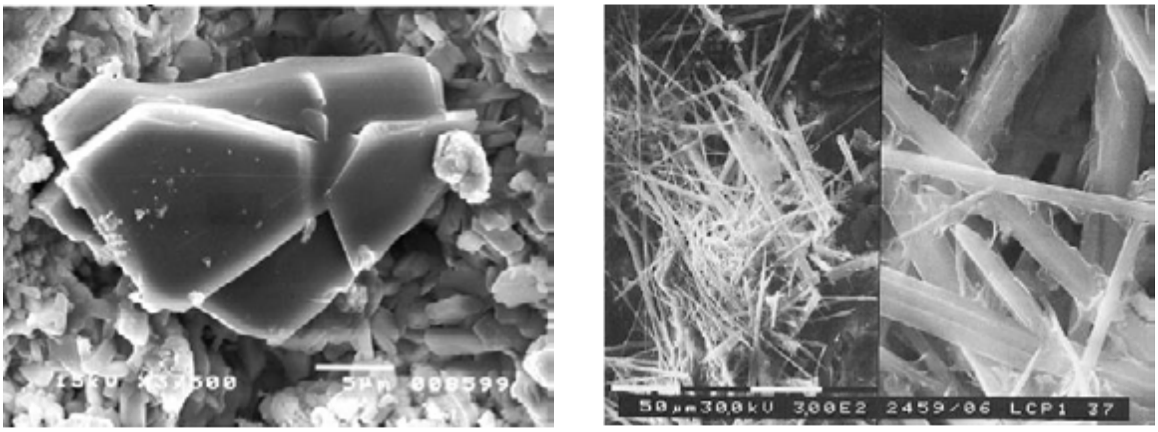


Figure 3: (Above) Interaction of concrete with sulphuric acid 20 (Below) SEM image of (left) gypsum crystals and (right) ettringite with many other sulphur compounds (far right image shows higher magnification) [29].

SRB- Since mid 1930s it has been tried to explain MIC as induced by sulphate reducing bacteria in pure electrochemical terms. In 1934 VonWolzogen Kuhr and Van der Vlugt suggested what that then was called "cathodic depolarisation theory" or "classical theory". This theory can be summarized as below:

METAL:

Anodic reaction: $4Fe \longrightarrow 4Fe^{2+} + 8e^-$

Electrochemical cell

SOLUTION:

Cathodic reaction: $8H^+ + 8e^- \longrightarrow 8H_{ad}$

Cathodic reaction $8H_2O \longrightarrow 8H^+ + 8OH^-$

Electrolyte

MICRO-ORGANISM

$SO^{2-}_4 + 8H_{ad.} \longrightarrow S^{2-} + 4H_2O$

Microbial depolarisation

$Fe^{2+} + S^{2-} \longrightarrow FeS$

Corrosion products

$3Fe^{2+} + 6OH^- \longrightarrow 3Fe(OH)_2$

Corrosion Products

$4Fe + 4H_2O + SO^{2-}_4 \longrightarrow 3Fe(OH)_2 + FeS + 2OH^-$

Overall reaction

In the absence of oxygen, the cathodic areas of a metal surface quickly become polarised by atomic hydrogen. In anaerobic conditions the alternative cathodic reaction to hydrogen evolution, such as oxidation by gaseous or dissolved oxygen, is not available either. These conditions will result in the dissociation of water as to become the main cathodic reaction with the hydrogen ions thus produced both adsorbed on the metallic surface (polrisation) and consumed up by hydrogenase enzyme. Although the classical theory has been able to explain MIC by SRB for the first time on the basis of electrochemistry, many modifications of it along with new theories, to which we collectively refer as "alternative theories", have been put forward, details of these theories and advances regarding new theories have been discussed elsewhere [14, 16].

As an example, Figure 4 shows corrosion products formed on carbon steel exposed to SRB-only conditions and the spot analysis of the corrosion products. The results show formation of iron sulphide that is cathodic to the underlying steel, thus causing pitting in the steel.

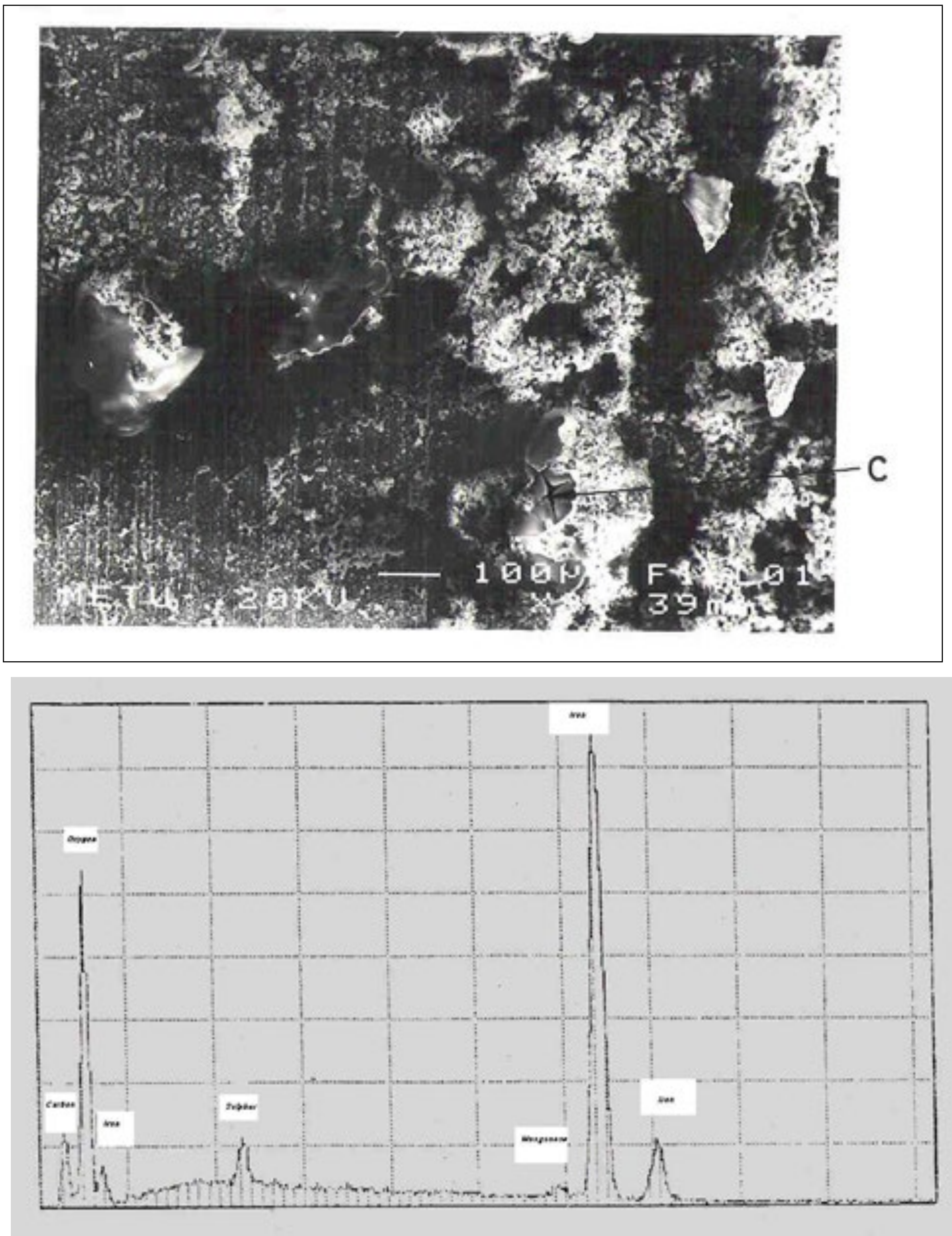


Figure 4: Corrosion products formed on carbon steel exposed to SRB-only culture (exposure time: 2600 hours). Left picture shows the pits formed and the spot analysis of point C (within one of the pits), as shown on the right-hand side figure, confirms iron sulphide formation [30].

Cyclic Effect of SRB-SOB Microbial consortium:

Seawater, in particular, contains many micro-organisms of which SRB and SOB are just two examples. When seawater is kept motionless in a container, due to microbial activity, it can lead into a low pH and producing of anaerobic conditions [31]. Normally what happens is that the aerobic SOB depletes oxygen, thus making the conditions more suitable for the SRB to become active. In this way, a cycle starts in which one type of bacteria feeds the other and gets fed back so that the cycle repeats itself. Such cyclic interaction has been seen in many other systems such as buried pipelines and Accelerated low water corrosion (ALWC) as experienced in marine piled structures, as briefly shown in Figure 5.

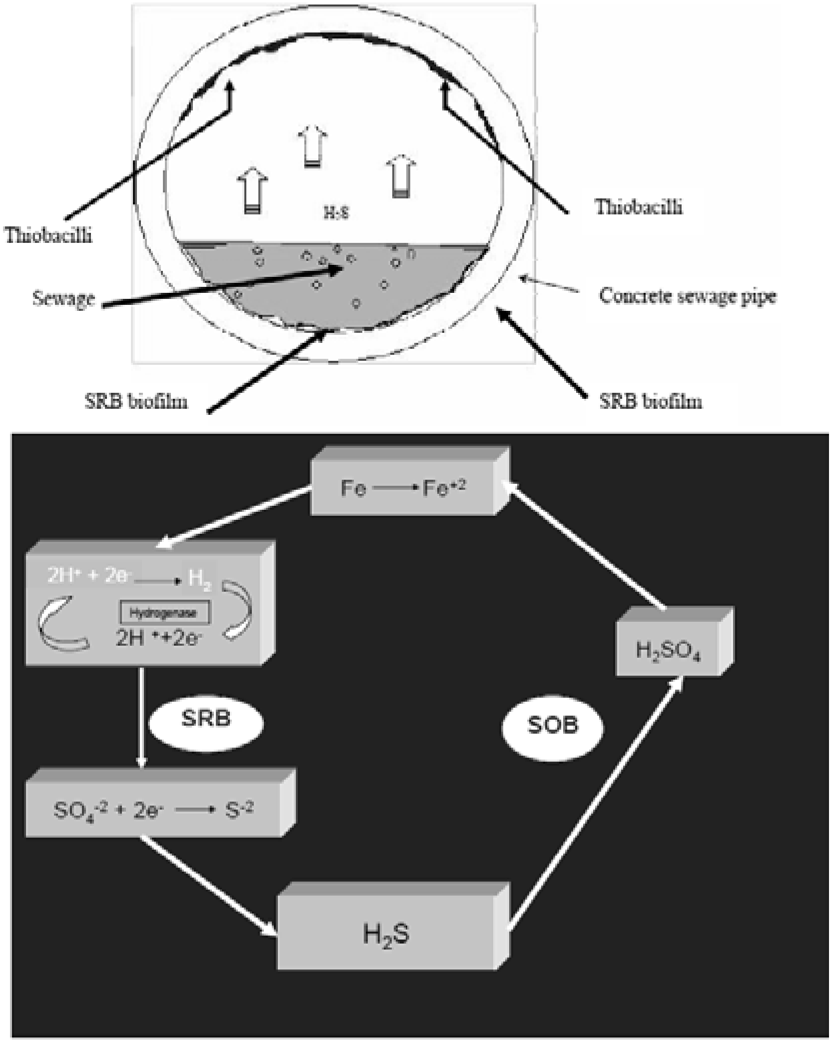


Figure 5: Cyclic effect of SRB and SOB: (Above) Cyclic effect of SRB and SOB in sewage systems, (middle) how a buried pipeline based on the environmental factors is exposed to corrosive effects of both SRB and SOB (Below) an example of cyclic effect of the bacteria involved in ALWC [14, 19, 32].

In this regards, when SRB and SOB are present, one will assist the other to make corrosion even worse. A possible consortium mechanism between SRB and SOB is shown in Figure 6.

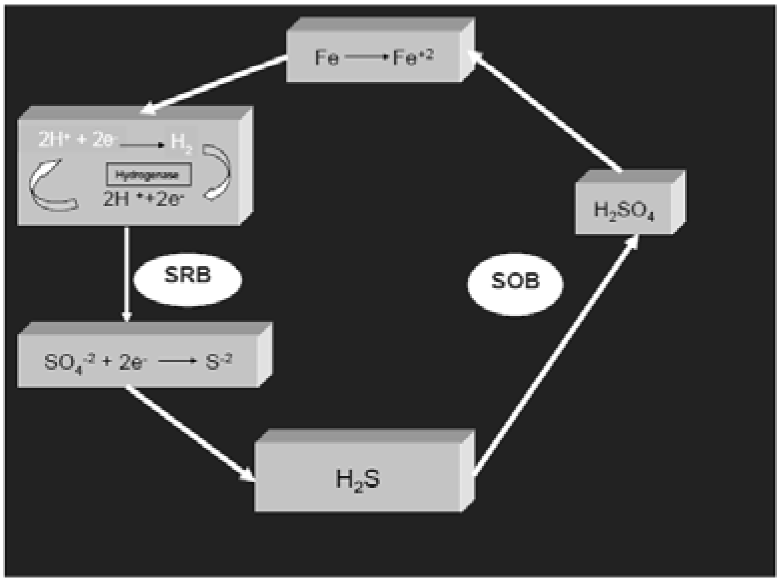


Figure 6: Schematic presentation of a cyclic interaction between SRB and SOB14 that may happen in a microbial consortium of the two [20].

Mitigation/Prevention Methods and Technologies:

When such a cyclic action between SRB and SOB occurs, the only way to break the cycle is to eliminate one, or even better, both bacterial species involved. Having this in mind, one should also notice that it is not yet known if MIC/MID can be taken as an end-result of non-microbial corrosion (an example of which being galvanic corrosion• that, obviously, has no contribution of the bacteria) or an already existing non-microbial corrosion can be further enhanced by the corrosive action of the bacteria. These approaches in design philosophy of CGBS platforms, for example, can be translated as the following scenarios:

a) "MIC/MID First" Scenario: This scenario puts all the importance on identification of possible sources of microbial contamination so that by taking appropriate counter-measures, MIC/MID will become too unlikely to happen. It must be noted that in this scenario, conventional means to mitigate/prevent non-microbial corrosion is not overlooked; they are just given a second importance with regards to MIC/MID prevention/mitigation policies.
b) "MIC/MID Last" Scenario: In this scenario, obviously, it is believed that by preventing/mitigation non-microbial corrosion, the chance for MIC/MID will also become too low.

The importance of this classification in design philosophy will be that if we believe that MIC/MID starts when non-microbial corrosion starts (that is, an "MIC/MID Last" Scenario) , then the best strategy to prevent MIC/MID will be by applying conventional methods to prevent/mitigate corrosion. These methods can range from applying cathodic protection to using coatings and/or change in design or working conditions. However, if we believe that when MIC/MID starts, that will be followed by non-microbial corrosion (an "MIC/MID First" Scenario), then the measures to be taken must focus more on preventing/mitigating MIC/MID than paying attention to non-microbial corrosion. This would mean putting more emphasize on application of biocides-if applicable- or modification of design/working conditions.

One natural question that may come to mind is whether it is not possible to have both scenarios together in place? Is it not possible that both MIC/MID and non-microbial corrosion mechanisms could exist together? It seems that, at least at early stages of corrosion, just one of the scenarios may prevail based on the kinetics of the corrosion reactions involved. Important reasons to back up this point is that mere existence of corrosion-related bacteria may not be taken as a sign of likelihood of MIC; as they may be there because of corrosion and not to cause corrosion via receiving energy from oxidising or reduction of the ions produced by corrosion reactions [33]. Also, under certain circumstances, the bacteria may actually decelerate corrosion instead of accelerating it [34, 35]. The important point, however, is that while at the early stages of the life of the CGBS, there could be either of scenarios prevailing, by aging, MIC/MID will always be a part of the corrosion scenario, sooner or later. It, then, can be followed that even if so far no significant sign of MIC/MID has been observed in operating the CGBS platforms, it is prudent to take care of all possible measures against this type of corrosion.

Some of the applied measures against the possibility of MIC/MID in CGBSs are as follows:

1. Water Displacement
2. Oxygen blowing (Air Sparging)
3. Making Holes in Legs
4. Use of Biocides
5. Applying CP
6. Applying Coatings on the reinforcement rebar and the Concrete
7. Careful make of the concrete

As it can be expected, from an MIC/MID point of view, the main aim of the first three practices, i.e., water displacement, air sparging and making holes in legs is to provide enough oxygen to replace the oxygen consumed by aerobic bacteria such as SOB. In other words, these methods assume that the main problem is NOTcoming from the aerobic SOB. These methods take it for granted that the main damage to the concrete structure is coming from SRB. Therefore, by oxygenation, the situation must not be let anaerobic (oxygen-free) and thus suitable for SRB activity. Here the main attempt to break the cyclic effect of corrosion enhancement by SRB-SOB consortia has been eliminating one (SRB).

However, as we have already shown in our discussion of the cyclic effect of SRB and SOB, unless one species is completely removed, any attempt to make a change may actually work for the other side. In the particular cases of interest, supplying the oxygen consumed by the anaerobes to prevent the environment anaerobic enough for SRB proliferation, may actually promote –or sustain- the growth of SOB.

A review of both field and laboratory investigations about the feasibility of practices such as oxygenation and de-oxygenation has addressed the following results [36]:

Oxygenation:

- When SRB are in the biofilm, the oxygen will be removed by other micro-organisms such that SRB can still survive in aerated environments,
- Oxygen has the ability to exacerbate corrosion by itself,
- Most reported cases of SRB-induced corrosion have happened when some dissolved oxygen was present in the bulk medium.

De-oxygenation:

- While field practices of oxygen removal have shown a decrease in the rate of uniform corrosion of carbon steel by 90%, when de-oxygenated conditions are not maintained properly, so that cycles of oxygenated-hypoxic conditions occur, can cause higher corrosion rates in carbon steel in comparison with cycles of either consistently aerobic or deoxygenated conditions.
- Under prolonged (over one-year) laboratory conditions, comparing corrosion resulting from stagnant aerobic natural seawater with that of resulting from stagnant anaerobic natural seawater showed that:
    - o Corrosion was more aggressive under totally anaerobic conditions,
    - o Under aerobic conditions corrosion was uniform whereas under anaerobic conditions, the corrosion was localised pitting.

Thus, while de-oxygenating the conditions is definitely not a good option, oxygenation by its own can not be considered as an ideal solution to the possible problem of MIC/MID.

Oxygenation is definitely not a good choice for a "MIC/MID last "scenario. The reason is that if the situations have been evaluated wrongly so that biofilm has been formed and SRB have been accommodated already, oxygenation may not be a feasible way of handling the problem as it may not reach under the biofilm to immobalise the SRB. It must also be noted that in this scenario if enough measures are not taken, uncontrolled over-oxygenation may cause more problems than it is supposed to solve.

These shortcomings and disadvantages will call for incorporating other measures. One of these measures is using bactericides(biocides). However, there are mainly three disadvantages associated with biocides no matter how effective they might be in handling potential and existing MIC/MID in CGBS platforms:

1. Due to large amounts of water to be handled, biocide overdosing and long wait periods for a good mix can be expected [14]. This will definitely have unwanted impacts on the economical feasibility of using biocides.

2. There are mainly two types of biocides; oxidising biocides (such as chlorine and its compounds) and non-oxidising biocides (such as Aldehydes). As normally oxidising biocides present better biocidal effects, they are to be treated with much more care. It must be noted that if biocides are to be used in conjunction with oxygenation practices such as water displacement, the biocide-containing water can present high hazardous conditions from an environmental point of view. In this respect, the biocide –whether oxidising or non-oxidising- will act like antibiotics: killing both "bad" and "good" bugs together without any discrimination. Also, while corrosion-enhancing bacteria such as SRB may be regarded as "bad bugs" from our perspective, they are certainly an integral part of nature, helping to sustain sulphur cycle. Therefore they are required in nature and can not be annihilated totally. It may be a good idea to try some chemicals that could have targeted -temporary biostat features, meaning that these chemical may sustain the growth and activity of, say, SRB and not other bacteria, under controlled conditions for a given time. Obviously, other such biostats could have been developed for other bacterial groups that are related to corrosion. Such biostats wouldn't kill the bacteria and just keep it under-activated for a certain period of time, thus helping maintain a better MIC/MID management of the CGBS platforms. However, at the moment, no such chemicals are present and under restricted environmental regulations, no biocide is to be used. However, despite all this there is another version of biocide use which is chlorination. One case where chlorine (along with copper) has been used on incoming fresh seawater has been Draugen GBS platform operated by Shell in the North Sea (Norway) [37]. The reported case was apparently an MIC/MID last case where the main corrosion magnitude of concern was due to non-microbial corrosion.

3. Cathodic Protection (CP): In simple terms, corrosion can be equated with what is called as "anodic reactions" in electrochemistry. When metals lose electrons, they become positive ions (the so-called "cation" as opposed to the negatively charged ions which are called 'anions"). Mechanical stability and strength of these positively charged ions are too low. Thus, when metals lose electron and become "anode", the resulting mechanical shortcomings cause (electrochemical) corrosion -or premature failure of the material. Therefore, if somehow these lost electrons can be given back to the metallic atoms, this will stop anodic reactions from happening-at least in theory. Cathodic protection aims at generating these needed electrons through methods such as impressed current (that will supply the needed electrons through producing currents) or sacrificial anodes (that will supply the electrons by letting other metals -that are both easier to corrode and economically much cheaper than the metal to be protected- go through anodic reactions and corrode and thus produce electrons).

While CP is a known and trusted measure against non-microbial corrosion, its application in MIC-related cases is still open to debate [38-40]. It is believed that CP can affect biofilm formation by three possible mechanisms, namely, (1) preventing bacterial adhesion onto the metallic surfaces, (2) increasing the repulsive electrostatic forces between the negatively charged steel surface and bacteria with the same negative charge and (3) elimination of the bacteria by increased pH due to CP-stimulated hydroxyl ion production. As Javaherdashti's review of the existing literature shows, application of CP may not always be the best possible choice. In other words, CP must not be solely relied upon when it comes to MIC [14].

One way that may be suggested to control MIC/MID, is to find a way to attract hydrogen ions before sulphide ions find the opportunity to react with them to generate hydrogen sulphide gas. There are two reasons for exclusion of hydrogen sulphide gas:

- This gas is highly poisonous so that having it in the system can form a serious threat against the health of the personnel. There are reported cases of serious health problems caused by hydrogen sulphide ranging from DNA damage to death [41, 42].
- It is a corrosive gas. Based on research, it has been reported that corrosion rates of steel in air-H2S mixtures is higher than in the air or H2S phases alone [43]. Also, laboratory data suggest that concrete exposed to H2S and sulphate has shown more severe (higher corrosion rates) than those concrete samples exposed to the H2S gas alone [44]. These findings may also suggest that hydrogen sulphide gas must be in combination with something (oxygen-in the case of steels- and sulphate-in the case of concrete) to become highly corrosive.

On the other hand, if sulphate (SO4-2) is reduced to sulphide (S-2) by SRB, in case these negatively charged anions can find ferrous (Fe+2) ions instead of hydrogen sulphide, black precipitates of iron sulphide will be produced. While iron sulphide is highly cathodic to steel (and thus its formation on steel will corrode the underlying steel very fast), no corrosion impact of iron sulphide on concrete has been reported yet [45]. This point will later be used in this review to propose a possible new mitigation method.

Coating of the steel rebar and/or concrete:

The first measure against corrosion of steel in the RC structures is the concrete itself. However, it is possible to either coat the steel or the concrete, or both. A rather known method is to use epoxy-coated steel rebar. One recent method is by using chemical conversion to create phosphated steel rebar where the phosphate film around the reinforcement is dissolved to result in formation of a dense, protective coating [46]. Also, non-toxic, biocide-free, silicon surfaces [47, 48]. New technologies such those that use of micro-fine copper flakes in epoxy resin to be then sprayed onto concrete bricks seems to be promising in order to reduce biofilm adhesion [49]. The leaching range of copper from copper/epoxy coatings has been between 0.055 g/cm2/ day (for Cu Coating) to 0.012 g/cm2/ day (Cu coating+base+biocide). However, considering the environmental concerns and sensitivities governing the operation of CGBS platforms, use of such technologies must be taken with great precaution. As with biocides, copper is capable of killing micro/macro-organisms (if it can get into the organism's body), no matter if it is SRB or a useful organism necessary for the marine ecosystem. Another very important factor in applying coating is the cost: while coatings such as 100% solid polyurethane coating as well as PVC and coal tar epoxy coatings all are ticked when it comes to considering factors such as application method and field repairability, other factors such as safety and environmental concerns as well as cost must be considered very carefully [50].

4. Careful make of the concrete: perhaps the most important of all factors mentioned so far is the way the concrete is made in the first place. Some of te most important factors in this regards are, but not limited to, as follows [51]:

- In case of concrete structures in particular, care must be given to the quality of the mix water. A very interesting case has been reported where some of concrete coumns of an occupied building (a hospital) showed severe SRB-induced corrosion as a result of possible contamination of the mix water with SRB. Use of good quality mix water. While this means a maximum total dissolved solids (TDS) of 500 mg/l and pH range of 6.0 – 8.0, this criteria also means using a mix water treated with some sort of biocides to render it more suitable from a microbiological point of view.
- To decrease the likelihood of MIC even further, a Low water-to-cement proportion (max.0.6 and in some especial cases less than 0.5), in this way the concrete becomes less wet so less likely for the bacteria to proliferate. Also, in this way the concrete durability is increased providing better cover for reinforcing.

Apart from such conventional methods, new research can also bring about new avenues. One example of such is the so-called anti-bacterial stainless (ASS) with martenstic microstructure that is using controlled copper ion implantation [52]. This steel-despite its broad-spectrum antibacterial effects, is not suitable for use in chloride-containing environments, thus making it an inappropriate choice for use in marine environments. However, in this context of innovative solutions, the authors would like to suggest a practice that may prove to be useful. This practice could be as follows:

Assume that in the CGBS platform, oxygenation methods are used to compensate the oxygen used by the aerobes to avoid anaerobic conditions that may promote SRB activity. Also assume that iron is added into the incoming seawater (which-compared with copper which has been suggested for use in Draugen platform- is not a poisonous metal for organisms). When this iron comes to contact with freshly oxygenated sweater, will be oxidized readily to ferrous. By bio-augmentation (adding certain micro-organisms along with their favourite "food" deliberately into the environment) of iron reducing bacteria (IRB)- that reduce ferric to ferrous - into the incoming sweater, any existing ferric ion –existent perhaps as a result of uncontrolled oxygenation of ferrous ions- will be reduced to ferrous ion [14, 36, 53]. Thus in the stagnant conditions of the storage tanks or platforms legs, the concentration of ferrous ions will be increased continuously.

Furthermore, by likening stagnant seawater conditions to the batch growth conditions, if local concentration of ferrous irons increases, specially in the presence of IRB that has known corrosion-deceleration properties4, it may be likely to control corrosion more effectively as the conditions would turn into protective instead of aggressive [14]. If there is an effective CP system in place, it will change the polarity of iron sulphide with respect to the underlying steel so that the iron sulphide will start to act like an anode with respect to the cathodic underlying steel.

The above is a suggestion that needs to be put into carefully scrutinized practice before it is actually applied so that its feasibility can be calculated effectively, Some of the immediate advantages of this proposed method can range from not releasing poisonous metals such as copper into the environment to use of a natural agent (such as IRB) to control possible MIC/MID problems. Currently, initiations for testing this hypothesis has started at the Dept. of Civil Engineering, Curtin University.

Conclusions

The problems associated with MIC/MID in CGBS platforms can be very serious as the type of corrosion induced will most probably be of a localised nature. Currently, the measures taken against MIC/MID in such platforms are either oxygenation or application of CP. Coatings, too, may be employed. However, none of these counter-measures is ideal as they do have deficiencies that need to be clearly scrutinized and addressed during both design and operation. The mechanisms related to the MIC of carbon steel and MID of concrete- as main components of RC structures- and some critical aspects of MIC/MID countermeasures were discussed in this review.

Acknowledgement

The author would like to thank Dr. Roger King (Consultant, UK), Dr. John P. Broomfield (Broomfield Consultants, UK), Mr. Arnstein Godejord (Dr.techn.Olav Olsen Inc., USA), Dr. Fakhruddin Habiby (Trans-Northern Pipelines Inc., Canada), Mr. Rufus Ashiedu (Vermilion Oil and Gas Australia Pty Ltd., Australia), and Mr. Ali Sarandily (AECOM, Australia) for their kind review of the draft manuscript and their comments and recommendations.

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