RESEARCH PAPER
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The Role of Bacteria in Under-Deposit Corrosion In Oil and Gas Facilities: a Review of Mechanisms, Test Methods and Corrosion Inhibition

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1. Introduction

Under-deposit corrosion (UDC) represents a threat to pipeline integrity. This phenomenon has been appointed as responsible for localised corrosion damage in both laboratory testing[1-2] as well as in root cause analysis of critical pipeline failures[3-4]. UDC causes localised corrosion to form beneath the deposits which occur due to chemical and physical differences between the bare and deposited-steel surfaces[5] and, in case of fully deposited surfaces, as a result of the conditions under the deposits. Typically, horizontal or inclined sections of pipelines where the flow velocity is under its minimum limit tend to accumulate (usually at 6 o'clock position) corrosion products and scales of the line leading to deep penetration of the metal surface[6]. Under-deposit corrosion can frequently take place in sub-sea injection, transmission and well-fluid pipelines. However, it can also occur in cooling water systems with scales and foulants. Solid particles can promote corrosion in two ways: 1) adsorption of inhibitors onto deposits reducing inhibitors availability and thus leading to inadequate inhibition beneath the deposits[7], and 2) producing corrosion-erosion at high low velocities by either eroding the metal wall[8] or removing layers of corrosion products and filming inhibitors[9].

In addition to the presence of mineral deposits, microorganisms are commonly present in the systems aggravating the problems in pipeline integrity management. In real life scenarios, it is unlikely to find abiotic systems due to the ubiquitous nature of the microorganisms where some of them have the capability of degrading the metal as a result of their presence or activity leading to MIC. Microbial cells thrive in between solid particles deposited on the metal surface where they could grow protected to some extent from external threats[10] (e.g., leading to less effective biocide treatment in deposited areas). After this settlement stage, further corrosion complications arise from this combination of microbes and solid particles leading to both MIC-UDC damage. In this sense, we can define "UDC-MIC occurrence" as the combination of electrochemical, physical and microbiological processes compromising pipeline integrity.

Previous work using sludge deposited on steel surfaces demonstrated that microbes living within that deposit accelerated and induced general and localised corrosion[11]. A long-term study of UDC in stagnant seawater showed that samples with a deposited mix of magnetite, calcium carbonate and sand induced more localised corrosion than the deposit-free samples[12]. The microbe-deposit combinations were also found responsible for pipeline failure in a production system[13]. Similarly, UDC in an injection water pipeline has been associated with the premature failure due to multiple factors, including the presence of microorganisms in the system 3. Wang et al.,[12, 14] proposed a synergy between MIC and UDC which led to a more severe localised corrosion at half-pipe steel covered with mixed deposits under simulated stagnant seawater conditions.

Currently, diverse testing methods have been used to assess general and localised corrosion underneath inert deposits through electrochemical measurements[15-17]. However, the intrinsic complexity of electrically conductive deposits and biofilms can impart difficulty to the interpretation of the electrochemical data. From the microbiological point of view, emerging omics based-techniques open a world of possibilities for the understanding of biofilm-deposit-metal interactions. Omics refers to a field of study in biology which involves a group of technologies used to explore the roles, relationships, and actions of the different types of molecules that make up the cells of an organism. The techniques include: 1) Metagenomics (the study of genetic material of microorganisms from environmental samples to provide information regarding diversity and ecology of a specific environment); 2) Transcriptomics (study ribonucleic acid (RNA) molecules to identify which cellular processes are active and which are dormant); 3) Proteomics (identification and quantification of protein sets produced at a specific point in time); 4) Metabolomics (the study of complete set of metabolites that are the end products of cellular processes)[18]. Furthermore, microscopy and surface chemical analysis techniques have also been employed in the study of both UDC and MIC, but usually as a separate phenomenon. For MIC, these techniques provide valuable information about the involvement of biofilms in the biocorrosion process of metals and their alloys.

Research in UDC and its inhibition has achieved understanding about the effect of diverse deposits on steel surfaces, and also some insights into the role of deposits in corrosion inhibitor performance. However, the microbial-deposit-metal relationship and how this combination impacts corrosion processes has not been investigated to a great extent. Similarly, there is a knowledge gap regarding the effect of biofilms and their extracellular polymeric substances (EPS) on inhibitor efficiency and conversely the potential biocide effect of some inhibitors on the integrity and activity of microorganisms. The following is a review of available literature regarding MIC and UDC in oil and gas pipelines. This work aims to connect these two phenomena which impact steel asset integrity. The review includes traditional and new testing techniques for both UDC-MIC as well as diverse mitigation strategies.

2. Under-Deposit Corrosion

2.1. Major factors influencing corrosion under deposits

2.1.1. Nature of deposit

The deposits found in oil and gas facilities are classified according to their nature as follows 1) inorganic deposits, e.g., sand, corrosion products, and scales. 2) organic deposits, e.g., asphaltene, wax, biofilms and, 3) mixed deposits as "schmoo" a thick black layer covering the internal wall of the pipeline[9]. A previous study showed that silica sand decreased general corrosion by a factor of 3 to 5 at both 25°C and 80°C. The authors state that the inert sand creates a mass transfer barrier for corrosive species as well as a decrease in anodic and cathodic currents due to less active available surfaces 5. However, some researchers have demonstrated that sand decreased general corrosion but also created localised attack under the sand-deposited area[19-20]. In real oil and gas scenarios, the solid particles deposited in the bottom of the pipeline have a diverse and complex composition which can determinate the type of UDC. For instance, Pandarinathan *et al.*[2] evaluated three typical constituents of pipeline deposits (sand, alumina and calcite). The authors demonstrated that general corrosion occurs depending on the type of the

deposit. The most corrosive deposit was alumina, followed by calcite and the less corrosive silica sand. Another common deposit present in pipelines is iron sulphide (FeS) which has been found to be more corrosive to X-65 carbon steel than the inert silica sand under H_2S environment[21]. Another UDC study demonstrated more severe general and localised corrosion underneath a field sludge deposit compared to a sand deposit[22].

2.1.2. Pipeline dimensions
Been *et al.*[23] mentioned that combined gravitational force in which solids settle to the bottom of the pipe and the dynamic of the fluid could lead to UDC at unusual locations in the line. The author also stated that the location, quantity and structure of the deposit layers formed could be different in large diameter lines (>500 mm) compared to small diameter lines (<250 mm).

2.1.3. Deposit features
The particle size of the deposit seems to influence the extent of the damage, with the smaller silica sand particles (diameter less than 44 µm) being less corrosive than larger sand particles (250-750µm)[24]. Results from with carbon steel under CO_2 covered with deposits of glass beads, SiO_2 powder and sand indicated that at higher deposit porosity higher corrosion rates occurred[25].

2.1.4. System conditions and chemical treatments
Undoubtedly, the presence of chemicals such as corrosion inhibitors, biocides, scale inhibitors, wax, and asphaltene amongst others will influence localised corrosion formed underneath deposits. Other determining factors include gas presence (CO_2, H_2S, O_2), electrolyte corrosiveness (pH, salinity, acetic acid, sulphur), oil/water ratio, temperature and pressure[9].

3. Microbiologically Influenced Corrosion:
It is well-known that microbial cells can either directly or indirectly influence the corrosion processes leading to metal deterioration. The indirect mechanism, also known as "chemical microbially influenced corrosion (CMIC)" occurs when microbial cells change the surrounding environment, e.g., producing corrosive species such as acids and sulphides. The direct mechanism includes 1) direct electron uptake or "electrical microbially influenced corrosion (EMIC) [26] and 2) by biofilm deposition on the steel surfaces influencing anodic or cathodic reactions[27]. The effects of microorganisms or their activity on metals with deposits can be as follows: 1) biofilms act as organic deposits changing physically and chemically the surrounding environment even though these microorganisms are not metabolically related to corrosion; 2) microbial cells can change the properties of the solids previously deposited on the steel; 3) corrosion microbial activity leading to formation and deposition of corrosive species[28]; 4) creation of microenvironments underneath the biofilm as a result of extracellular polymeric substances (EPS) formation. The EPS mediates cell adhesion by forming a three-dimensional network that immobilizes cells within the biofilm[29]. Also, the effect of EPS on the corrosion of carbon steel has been related to the presence of acidic groups in this matrix, which increases the corrosion on steels by lowering the interfacial pH[30]; 5) microorganisms can also degrade the structure of corrosion inhibitors and coatings by utilising their constituents as carbon sources[28].

3.1. Typical metabolic groups associated with MIC
3.1.1. Sulphidogenic microorganisms
3.1.1.1. Sulphate-reducing prokaryotes (SRP)
This sulphidogenic group comprise sulphate-reducing archaea (SRA) and sulphate-reducing bacteria (SRB). SRBs have been historically associated with MIC problems because of their ability to reduce sulphate to sulphide and consequently iron sulphide (FeS) formation which can be highly corrosive[31]. Additionally, some strains of SRB can uptake electrons directly to the metal surface producing EMIC which is considered as an efficient MIC process[32].

3.1.1.2. Sulphur-reducing bacteria (S°RB)
SoRB can reduce elemental sulphur (S°) to hydrogen sulphide (H_2S) to produce energy and, iron sulphide (FeS) when Fe ions are available. S°RB can also ferment proteinous substrates, organic acids and single amino acids to produce ethanol, acetate, propionate, isovalerate/2-methyl butyrate, H_2, and CO_2[33]. *Thermovirga lienii* is one of the most representative SoRB related to MIC process both experimentally as well as in case studies of failure, where it was classified as high-risk microorganism due to its predominance within deposits covering highly corroded steel surfaces[34].

3.1.1.3. Thiosulphate-reducing bacteria (TRB)
TRBs disproportionate thiosulphate to produce sulphate and sulphide which eventually form iron sulphide (FeS)[35]. This microbial metabolic group has been cited numerously in MIC literature, especially *Thermoanaerobacter* genus. A recent MIC-UDC work showed that fermenting-TRB considerably enhanced localised attack underneath an oilfield deposit[36]. *Thermoanaerobacter* species can also use diverse fermentation pathways producing hexoses, ethanol, acetate, lactate, H_2, and CO_2[37].

3.1.2. Fermentative microorganisms
This metabolic group obtain energy from a wide range of organic compounds, including sugars, peptides, amino acids, or organic acids. Some can also use inorganic sulphur compounds, ferric iron, and nitrate as electron acceptors to oxidise their substrates[38]. Thus, those who use sulphur compounds as an electron sink during fermentation can contribute to H_2S production. Fermenters influence corrosion by producing different volatile fatty acids such as acetate formic and lactic, with acetate being the most common end product formed. The high corrosivity of acetic acid has been largely studied[39] and the widespread distribution of acetogens in oilfield CO_2 environment make these type of fermenters as a fundamental group involved in MIC problems. Typically, acetogenic bacteria ferment carbohydrates and oil hydrocarbons producing acetic acid which can precipitate on steel surfaces creating a local acid environment[40]. Acetogenics can also produce acetic acid using H_2 and CO_2 to synthesise acetyl-CoA[41]. Recently, Kato *et al.*[42] proposed the link acetogenesis-MIC with a *Sporomusa* sp. strain cultured acetogenetically using Fe^0 as a sole electron donor. Additionally, the organic acids produced by fermenters can be metabolised by SRB growth, nitrate- and/or iron-reducing bacteria inhabiting oil reservoirs establishing cooperation between these metabolic groups[38].

3.1.3. Iron-oxidizing bacteria
These microorganisms generate energy oxidising ferrous ions to ferric ions which precipitate as ferric oxides[43]. Starosvetsky *et al.*,[44] demonstrated that localised corrosion occurred in the presence of IOB, which resulted in a crevice effect caused by biogenic ferric oxides deposited on stainless steel surfaces. Anaerobically, some IOBs can reduce nitrate (NO_3^-) and oxidise ferrous iron (Fe^{2+}) 45 this efficient denitrification performance can potentially affect nitrate-based corrosion inhibitors. The EPS produced by IOB has been found to accelerate corrosion on carbon steel surfaces[46].

3.1.4. Iron/manganese reducing bacteria (IRB/MRB)
IRB/MRB reduce solid Fe^{+3} and Mn^{+4} oxides to soluble Fe^{+2} and Mn^{+2} ions. *Geobacter* and *Shewanella* genera have frequently been linked to corrosion and metal reduction. The role of metal-reducing bacteria towards steel corrosion is related to the removal of passivating layers of Fe^{+3}/Mn^{+4} oxides, which leads to localised corrosion by the exposure of metal surfaces to corrosive species.

3.1.5. Methanogens
Methanogenic archaea have become an important microbial group in the MIC field. They use molecular hydrogen (H_2) to reduce CO_2 and produce methane (CH4)[47]. These hydrogenotrophic microorganisms consume cathodic hydrogen in a process called "cathodic depolarisation" which contribute to steel corrosion[48]. Methanogens have also been identified as electromethanogenic microorganisms able to induce EMIC by extracellular electron transfer (EET) uptaking electrons directly from the steel and hence accelerate corrosion[49].

3.1.6. Syntrophic relationships
The interest for microbial syntrophic (cross-feeding) associations in MIC has grown in the recent years. These associations are not referred only to the transfer of reducing agents such as hydrogen or formate; they can also include the exchange of organic, sulphur and nitrogen compounds as well as the removal of toxic agents[50]. Although it is difficult to interpret the precise mechanism(s) in which microbial associations contribute to MIC, it is expected a metabolic interaction between microbial partners could thrive and eventually affect metal integrity in oil fields. The most cited syntrophy in MIC research is between sulphate-reducing prokaryotes (SRP) and methanogens in which SRB convert lactate into acetate and hydrogen, both of which are subsequently utilised by methanogens for the production of methane[51-53]. Another biocorrosion study associated the presence of hydrogen-utilising methanogens, sulphur and thiosulphate reducing bacteria, fermenting bacteria and iron reducing bacteria, with important corrosion problems in Alaskan North Slope Oil Facilities[54].

4. UDC-MIC Testing Methods

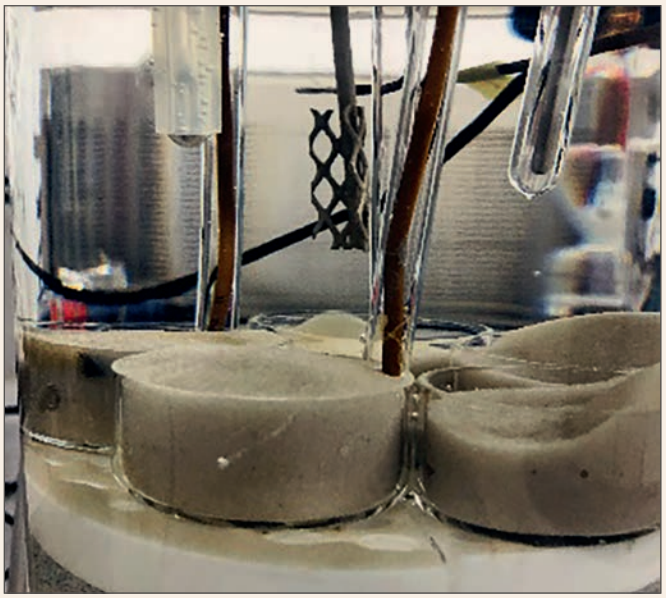

Figure 1. Sand-deposited carbon steel samples immersed under biotic conditions in CO_2/N_2 containing solution. Suarez et al, (unpublished results).

Figure 2. Three electrode set-up for UDC-MIC testing after 4 weeks of immersion under biotic conditions Suarez et al, (unpublished results).

Selecting appropriate techniques to determine electrochemical reactions involved in UDC-MIC is challenging because of the multiple and complex variables involved in a deposited system. For UDC, several laboratory techniques that simulate field conditions have been adapted. Vera *et al.*[9] listed and compared testing methods in their UDC review. Other methods, such as scanning probes, radiography, ultrasonic testing, field signature and electrical resistance probes, amongst others can be suitable techniques to evaluate UDC although some of them possess limitations[55].

Testing methodologies using test reactors have been used to assess both general and localised corrosion underneath deposits and in the presence of inhibitors by electrochemical measurements[15, 56]. Additionally, the susceptibility to localised corrosion of deposited surfaces can be assessed through accelerated electrochemical tests using this configuration[1]. This test methodology also allowed the study of UDC using different types of mineral deposits, e.g., sand, calcite, and alumina[2] as well as different coatings, biofilms and/or field deposits collected from industrial operations such as sludge, mixed mineral and oil deposits[36]. Recently, we studied the MIC-UDC phenomenon using a three-electrode test set-up (Figures 1 and 2) covering the samples with silica sand. The test solution was continuously replenished to keep microorganism active during the experiment. After the immersion period, the samples were maintained under continuous injection of N_2 to ensure complete drying before surface analysis (Data unpublished). The set-up was shown to provide a suitable method to evaluate the interactions between microorganisms and sand-deposits on corroding steel. Likewise, we have recently assessed biocide and inhibitor efficiency in the presence of sand deposits containing a microbial consortium (data unpublished). This study showed that deposits significantly decreased biocide efficiency and resulted in a faster re-establishment of injured biofilms.

Moreover, some techniques such as multi-electrode arrays can provide insights into the galvanic effects beneath the deposits and can be used for biofilms. Solid particles can provide different chemical and physical conditions underneath the deposit than those conditions on the bare steel resulting in galvanic cells forming between the two areas leading to localised corrosion. Various multi-electrode arrays has been used to investigate UDC. For instance, Turnbull *et al.*[57] developed an electrode array of 24 electrodes designed

for evaluating UDC inhibition. Tan *et al*.[58], Zhang et al.[59], Hinds *et al*.[60] and, Xu et al.[61] amongst others have also used microelectrode arrays with deposits to study UDC and/or its inhibition. Dong *et al*.[62] assessed the heterogeneous corrosion processes underneath SRB-biofilm.

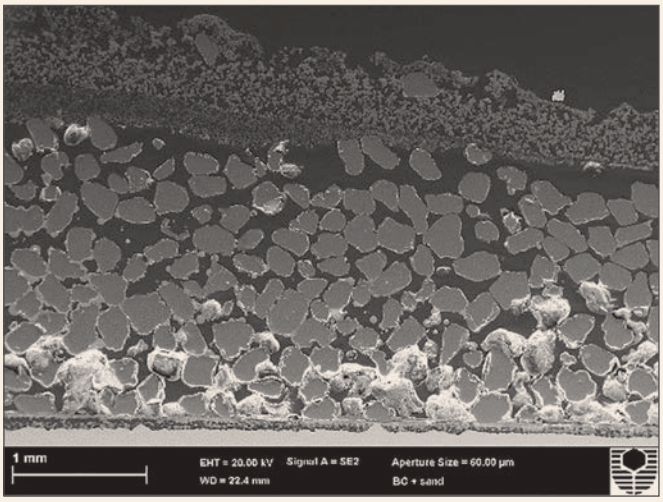

Figure 3. Image of a cross-section through a sand deposited-metal surface in the presence of a microbial consortium. Suarez et al, (unpublished results).

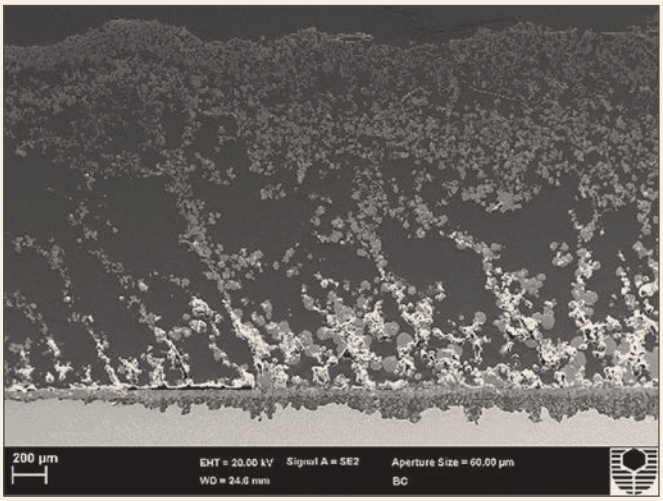

Figure 4. Image of a cross section through a sand-free metal surface in the presence of microbial consortium. Suarez et al, (unpublished results).

In regards to the microbiological component, several techniques have been developed to study microbe-metal interaction and how it influences corrosion of metals. Table 1 shows some MIC traditional and emerging methods, some of these methods can be suitable to study corrosion under deposits. Particularly, microscopy and surface chemical analysis are important tools for studying biofilm/metal interaction. Microscopy has been widely used to investigate the contribution of microorganisms to metallic corrosion. These techniques involved Field Emission Scanning electron microscopy (FESEM), 3D-profilometry, Atomic force microscopy (AFM), and Transmission electron microscopy (TEM)[63]. Microscopy can provide information about: 1) Biofilm contribution to corrosion, e.g., changes in the microstructure of the metal after cleaning of corrosion products 2) Biofilm development, distribution, adhesion and relation substratum/corrosion products; 3) Morphology of microorganisms and colony formation and distribution on the metal 4) SEM of cross-sectional- images reveal the profile of the damage[64] e.g., as presented in Figure 3 and 4 (steels covered and uncovered with sand deposits respectively). These SEM images of corroded steel specimens exposed to microorganisms showed corrosion products/deposits distribution, metal penetration and morphology of the damage under the deposits, and microbial cells (data unpublished). Surface analysis techniques, on the other hand, can provide surface chemical characterization, nano-scale analysis, and/or thin film characterisation[65-66]. The information about chemical composition of corrosion products, biodeposits and underlying layers formed (in cross-sectional images) contribute to the understanding of electrochemical mechanisms that take place as a result of microbial presence/activity towards steel corrosion.

Although some traditional microbiological techniques provide insight into microbial activity and corrosion processes, identification and role of the whole microbial community related to UDC and its inhibition has not been widely addressed. Gaining information about microbial community activity is probably a milestone in the understanding of corrosion mechanisms on deposited-steel surfaces. An Accelerated Low-Water Corrosion (ALWC) study in a European harbour determined diversity, distribution, abundance and activity of sulphate-reducing bacteria (SRB) within deposits obtained from carbon steel sheet piles[67]. The results showed that SRBs were more active in the inner and intermediate layers of the deposits and related to the presence of FeS in these layers. Emerging omics-based techniques can contribute to determining MIC microbial populations regarding diversity and metabolisms. These techniques have achieved significant progress in health sciences, and recently it has gained attention in MIC research. Beale et al.[18] stated that the bioinformatic approaches to MIC research provide information about microbial respiratory processes, metabolic reactions, corrosion mechanisms, pathways, microbial community structure and its activity. For example, the use of metabolomics techniques identified critical metabolomics biomarkers to predict MIC in copper pipes[68] as well as differentiation of samples due to the reduction of carboxylic acids produced by microorganisms with the potential to cause MIC problems[69]. It is expected that in the near future the exponential growth of the omics discipline will improve the understanding of microbe-metal-deposit interactions resulting in metal deterioration. For instance, transcriptomics could serve to establish differences in metabolic pathways of microorganisms between the surfaces of steels with deposits and those with no deposits. Similarly, metagenomics would be able to reveal differences in composition and structure of the microbial population in the presence and the absence of deposits and relate them to the development of corrosion.

From the practical point of view, it is essential to consider the sensitivity of microbial molecules (DNA, RNA, proteins) to degradation and change which requires strict preservation methods for accurate detection and quantification. In this way, it is important to highlight that to generate meaningful and reliable data, experiments should be ideally designed in the way to control aspects such as critical temperatures, sample replicates, samples handling, solution for molecules preservation, and processing times among others. Collecting and processing samples on-site, on the other hand, make these conditions more difficult to achieve. It is necessary to take extra effort on sampling to preserve molecules to be analysed as well as the deposit-steel interface for further characterisation and visualisation of the layers formed. It is also relevant to mention that to help diagnose MIC as part of UDC, analysis should target identification of microbial cells in such deposits.

Due to the complexity of a system containing deposits and microorganisms, interdisciplinary participation is essential when defining the laboratory test methodology. Ideally, a combination of methodologies should undoubtedly aid better understanding of a problem hypothesised in the laboratory or a problem faced in oilfield facilities. For instance, Been *et al*.,[23] described a testing protocol developed to evaluate the effectiveness of five inhibitors to mitigate UDC in the presence of bacteria at large diameter pipeline deposited with a sludge (oil, water, sand and microorganisms). The protocol included inhibitors filming effectiveness, partitioning studies, sludge corrosivity, and bacterial kill tests.

5. UDC-MIC Mitigation

Corrosion management programs in pipelines involve pigging and inhibitors treatment to mitigate internal corrosion. Chemical treatment is commonly used to mitigate UDC. Nonetheless, it is a challenging strategy because some inhibitors cannot penetrate the deposit, leading to unprotected areas underneath of the deposit. In fact, some inhibitors have been shown to enhance localised corrosion in the presence of deposits[58, 92]. Pandarinathan *et al*.[20] showed that some inhibitors such as thiobenzamide inhibited general corrosion (>90%) on steel with and without sand deposits, but could not provide protection against localized corrosion. Also, pyrimidine derivates have shown to be highly protective under sand deposits 15. It is important to mention that some mitigation strategies typically included in UDC programs can potentially serve to prevent or mitigate MIC (e.g., mechanical cleaning, use of coatings and adequate facilities design). Table 2 lists strategies commonly used for MIC mitigation in oil and gas facilities. It is relevant to mention that the majority of methods have limitations and some of them are not long-term effective[93] (e.g., chemical methods). Moreover, there is a lack of information regarding the effectiveness of some MIC mitigation methods in the presence of deposits (e.g., biocide treatments) which need to be addressed to cover both aspects.

Table 1. MIC testing methods and monitoring

	Description	References
Microbial culture testing	Cultivating microorganisms allows detection and semi-quantitative enumeration of corrosion-related microorganisms. Limitation: underestimate microbial population	NACE-TM0212.[70] NACE-TM0194.[71]
Biochemical assays	Measure compounds and enzymes of cells to estimate microbial population related to MIC. Adenosine triphosphate (ATP), Adenosine Phosphosulfate reductase (APS), Hydrogenase.	Little *et al*.[72], Beech *et al*.[64]
Physiological activity	Techniques to detect microbial activity by transformation of radiolabelled metabolic precursors.14C-labeled compounds have been used to quantify catabolic and anabolic activities linked to corrosion tubercles	Phelps *et al*.[73]
Traditional MMM techniques	Molecular microbiological methods (MMMs) are genetic techniques which are culture-independent such as PCR and qPCR to detection and/or quantification of microorganisms by DNA amplification.	Whitby *et al*.[74]
Omics-based techniques	Metagenomic techniques (identification and characterisation of the complete microbial population); Transcriptomics (gene expression-activity); Proteomics (proteins production) and, Metabolomics (metabolism)	Beale *et al*.,[18] Beech *et al*.[29] Machuca *et al*.[75]
Microscopy	Field Emission Scanning electron microscopy (FESEM), 3D-Profilometry, Atomic force microscopy (AFM), Transmission electron microscopy (TEM)	Beech *et al*.[76], Sheng *et al*.[77], Yves *et al*.[78], Fang *et al*.[79] Wikiel *et al*.[80]
Fluorescence microscopy	Examination of samples treated with dyes that fluoresce under specific wavelength. Biological stains such as acridine orange which permeates cells to attach to DNA and RNA. Fluorescent in situ hybridisation (FISH) probes used to identify and quantify species and groups of corrosion-related microorganisms. 4′, 6-diamidino-2-phenylindole (DAPI) is a fluorescent dye that binds to DNA allowing detection/ quantification of live and dead cells. Confocal laser scanning microscopy (CLSM) create three-dimensional images using fluorescent dyes, to determine surface contour and measure critical dimensions such as biofilm thickness.	Chen *et al*.[81], Mudali *et al*.[82]
Surface chemical analysis	Elemental composition of corrosion products and deposits originated from microbial activity. X-ray diffraction (XRD), energy dispersive X-ray (EDS), X-ray emission spectroscopy (PIXE), attenuated total reflectance Fourier transform infrared spectroscopy (ATR/FT-IR), X-ray photoelectron spectroscopy, time-of-flight secondary ionisation mass spectrometry (TOF-SIMS), Auger electron spectroscopy (AES), X-ray photoelectron spectroscopy (XPS)	Beech *et al*.[83], Boxer *et al*.[84], Ding *et al*.[85], Seyeux *et al*.
Isotope Fractionation	Sulphur isotopes (^{32}S and ^{34}S) present in the sulphate which is reduced resulting in ^{32}S rich sulphide as a result of microbial metabolism within the biofilm	Little *et al*.[86],
Electrochemical techniques to measure and monitoring MIC	No external polarization: galvanic couples, open circuit potential (OCP), electrochemical noise (ECN), Multielectrode array systems (WBE) Small external polarization: Linear polarization technique (LPR), Electrochemical impedance spectroscopy (EIS), Electrochemical frequency modulation (EFM) Large external polarization: potentiostat or potentiodynamic polarization curves and pitting scans.	Angell *et al*.[87], Little *et al*.[72], Dominguez *et al*.[88], Mansfeld *et al*.[89], Beese *et al*.[90], Ben-Yoav *et al*.[91], Hue *et al*.[62]

Table 2. Strategies for MIC-prevention/mitigation

Physical Methods

Description	References
Mechanical cleaning Brushing in production and injection lines, rubbing spheres for heat exchangers, blasting with sand, grit or water. Removal of sludge, scale, encrustations and biomass. Pipeline inspection gauge (pig) is also efficient in removing deposits, and it can record information about corrosion problems, metal loss and curvatures in the pipe wall.	Videla *et al.*[94]
Filtration /UV-radiation/ These methods can use an alternative to the traditional chemical treatments which sometimes are toxic, expensive and non- biodegradables. A combination of filtration and UV disinfection of seawater has been shown to decrease localised corrosion of susceptible alloys. Membrane filtration systems are commonly used to control biofouling. These systems use a wide range of anti-adhesion and anti-microbial strategies on the membranes. Sand screens which mechanically filter out sand while fluids flow.	Machuca *et al.*[95] Mansouri et *al.*

Chemical Methods (Biocides/Biocide enhancers, biofilm dispersants and corrosion inhibitors)

Description		References
Non-oxidizing biocides		
Glutaraldehyde	A traditional biocide used against fungi, algae and bacteria including SRBs biofilms. The functional group of glutaraldehyde acts against proteins of the cell wall and cytoplasm. It has large-scale application, a broad spectrum efficiency, biodegradability and safety profile.	Ganzer *et.al.*[97] Wen *et al.* Greene *et al.*[98]
Quaternary ammonium compounds (QUATS)	These form cationic compounds which act as biocides and corrosion inhibitors. Their detergent property dissolves lipids on the cell. QUATS also avoid the formation of polysaccharides.	Cloete *et al.*
Organo-sulphur compounds	These prevent energy transfer mechanisms critical for microbial growth. Some are pH sensitive suffering rapid hydrolysis which makes them not suitable for cooling water systems at pH > 8.	Londry *et al.*[99]
Tetrakis hydroxymethyl phosphonium sulphate (THPs)	This has biocidal properties against bacteria, fungi and algae. It has good compatibility with other chemicals. Dissolve iron sulphides. It has large-scale application, broad spectrum efficiency, biodegradability and, safety profile.	Talbot *et al.*,[100]. Wen *et al.*[101].
Biocides- new approaches		
D-Amino acids as (biocide enhancers)	These are biofilm dispersal agents which convert sessile cells to planktonic cells which are more susceptible to biocides. D-amino acids are enhancers of THPs and alkyldimethylbenzylammonium chloride but not for Glutaraldehyde.	Kolding *et al.*[102]. Xu *et al.* Jia *et al.*[103] Xu *et al.*
Chelators (biocide enhancers)	Ethylene-diamine tetraacetic acid (EDTA) is slowly biodegradable. Ethylene-diamine disuccinate (EDDS) is more biodegradable and not hazardous. EDSS enhances the effects of THPs and Glutaraldehyde. It also cuts down biocide dosages in SRBs biofilm treatment.	Wen *et al.* , Xu *et al.*
Norspermidine (biofilm dispersant)	This polyamine inhibits biofilm formation. The combination of D-tyrosine and Norspermidine reduces the EPS content and modify the matrix structure in microbial aggregates, converting sessile to planktonic cells.	Hobley *et al.*[104] Si *et al.*[105] Xu *et al.*
Bacteriophages for biofilm treatment	Bacteriophages can prevent biofilm formation, biofilm eradication. Phages are host specific thus phage cocktails are expensive but necessary field applications at large scales.	Gutierrez *et al.*[106] Eydal *et al.*[107]. Motlagh et *al.*[108]
Antimicrobial stainless steels	304L-Cu antibacterial stainless steel has strong MIC resistance against *E.coli*. Copper-containing 2205 duplex stainless steels (2205-Cu DSS) have shown high antibacterial efficiency and localised corrosion resistance under biotic conditions.	Lin *et al.*[109] Nan *et al.*[110], Xia *et al.*[111] Machuca *et al.*[112]

Other Methods

Description	References
Design	
Selecting the design of the appropriate pipeline is critical to minimize UDC-MIC occurrence. These strategies are focused on UDC but may help to mitigate MIC simultaneously. The strategies include; selecting corrosion resistance alloys, increase flow rates, avoid dead legs as well as low parts in the pipes as a preventive measure for deposits accumulation 9 and similarly, potential microbial accumulation.	

6. Conclusions and Future Prospects

Corrosion observed under deposits on steels in the presence of microorganisms is the result of synergistic effects of different microbial groups that act as a consortium and alter the metal surfaces, directly or indirectly 113. It is possible to describe "UDC-MIC" as the combination of electrochemical, physical and microbiological processes towards metal integrity.

This paper reviews some concepts, testing methods and monitoring techniques for UDC and MIC, and discusses MIC mitigation strategies. Future research is required to fill knowledge gaps. These include the effect of the microorganisms on inhibitor efficiency and inhibitor performance in the presence of microbial cells and deposits. MIC research should also focus on mechanisms of how syntrophic relationships relate to corrosion and, specific interactions between deposits and microorganisms which lead to metal corrosion.

It is clear that understanding microbial-deposit-metal interactions entirely is very ambitious. However, information obtained by traditional and emerging techniques suited to provide both UDC and MIC insights should surely aid in the understanding of this combination, and in the development of more effective strategies to mitigate this aggressive form of corrosion. The contribution of omics-based techniques applied to MIC-UDC opens numerous and promising possibilities in this field. For instance, elucidating biofilm–metal-deposit interactions at the molecular level will aid in the understanding of the contribution of the UDC-MIC mechanism, and will potentially facilitate the development of UDC-MIC monitoring programs for particular operating systems.

The complexity of deposited-systems, which makes more difficult the assessment of localised metal corrosion under organic/inorganic deposit layers, should promote the application of more suitable techniques/configurations able to study localised electrochemical processes. In this way, it would facilitate future research focus on the study of corrosion inhibitor performance under deposits and in the presence of microorganisms.

A broad consensus in regards to experience and knowledge of a particular system, is critical for selecting testing methods as well as for designing mitigation programs. An appropriate multidisciplinary approach is crucial to extend the lifetime of oil and gas pipelines potentially exposed to deposits and microorganisms.

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