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PROTECTION AGAINST MICROBIOLOGICALLY INFLUENCED CORROSION

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ABSTRACT

Microbiologically influenced corrosion (MIC) is one of the most complex forms of material degradation because it is not caused by microorganisms alone, but by the interaction between microorganisms, biofilms, electrochemical reactions, water chemistry, deposits, flow regime and engineering design. MIC affects pipelines, cooling-water systems, marine structures, storage tanks, medical and food-processing equipment, sewage systems and buried metal constructions. The main danger of this type of corrosion is its localized and often hidden nature: deep pits may develop under biofilms or deposits while the external surface seems relatively intact. This article analyzes current approaches to protection against MIC with emphasis on prevention, monitoring and integrated corrosion management. The study is based on a narrative review of scientific literature, standards-oriented technical materials and recent reviews on microbial corrosion control. The results show that no single method can reliably prevent MIC in all environments. Effective protection requires a combined strategy that includes correct material selection, hygienic design, coating and lining systems, water chemistry control, removal of deposits, biocide or biological control programs, cathodic protection where applicable, regular monitoring of corrosion rate and microbiological activity, and systematic maintenance. The article concludes that the most rational protection against MIC is not reactive repair after leakage or failure, but risk-based prevention supported by continuous diagnostics and interdisciplinary cooperation between microbiologists, corrosion engineers, chemists and maintenance specialists.

Keywords: microbiologically influenced corrosion; MIC; biofilm; corrosion protection; biocide; cathodic protection; coating; pipeline corrosion; corrosion monitoring; industrial safety.

АННОТАЦИЯ

Микробиологически обусловленная коррозия (МИК) — одна из наиболее сложных форм деградации материалов, поскольку она вызывается не только микроорганизмами, но и взаимодействием между микроорганизмами, биопленками, электрохимическими реакциями, химическим составом воды, отложениями, режимом потока и инженерными решениями. МИК поражает трубопроводы, системы охлаждения, морские сооружения, резервуары для хранения, медицинское и пищевое оборудование, канализационные системы и подземные металлические конструкции. Главная опасность этого типа коррозии заключается в ее локализованном и часто скрытом характере: под биопленками или отложениями могут образовываться глубокие ямки, в то время как внешняя поверхность кажется относительно неповрежденной. В данной статье анализируются современные подходы к защите от МИК с акцентом на профилактику, мониторинг и комплексное управление коррозией. Исследование основано на обзоре научной литературы, технических материалов, ориентированных на стандарты, и последних обзоров по контролю микробной коррозии. Результаты показывают, что ни один метод не может надежно предотвратить МИК во всех средах. Эффективная защита требует комплексной стратегии, включающей правильный выбор материалов, гигиеническое проектирование, системы покрытий и футеровки, контроль химического состава воды, удаление отложений, программы биоцидной или биологической защиты, катодную защиту (где это применимо), регулярный мониторинг скорости коррозии и микробиологической активности, а также систематическое техническое обслуживание. В статье делается вывод, что наиболее рациональной защитой от микробиологически индуцированной коррозии является не реактивный ремонт после утечки или отказа, а профилактика, основанная на оценке рисков и подкрепленная непрерывной диагностикой и междисциплинарным сотрудничеством микробиологов, инженеров-коррозионников, химиков и специалистов по техническому обслуживанию.

Ключевые слова: микробиологически индуцированная коррозия; МИК; биопленка; защита от коррозии; биоцид; катодная защита; покрытие; коррозия трубопроводов; мониторинг коррозии; промышленная безопасность.

INTRODUCTION

Corrosion is commonly understood as the gradual destruction of metals through chemical or electrochemical interaction with the surrounding environment. However, in many industrial systems corrosion cannot be explained only by oxygen, salts, acidity or mechanical stress. In water-containing environments, microorganisms can attach to metal surfaces, produce extracellular polymeric substances, form biofilms and change the local electrochemical conditions. This phenomenon is known as microbiologically influenced corrosion, or MIC. The term does not mean that microorganisms create a completely new form of corrosion; rather, they accelerate, redirect or localize ordinary corrosion reactions through their metabolic activity and biofilm structure [1,2].

MIC is especially dangerous because it often develops beneath deposits, scale, sludge or biofilm layers where routine visual inspection is difficult. A pipe wall may appear acceptable from the outside, while localized pitting progresses inside the system. In pipelines and industrial water networks, such pits may develop into leakage, unplanned shutdowns, contamination of products, environmental damage and high repair costs. The problem is therefore not only a chemical or microbiological issue; it is also an engineering, economic and safety problem.

The microorganisms involved in MIC may include sulfate-reducing bacteria, acid-producing bacteria, iron-oxidizing bacteria, iron-reducing bacteria, nitrate-reducing bacteria, methanogenic archaea and fungi. These organisms do not act in isolation. In real systems they usually form mixed communities embedded in biofilms. Within the biofilm, oxygen concentration, pH, ion distribution and redox potential differ from the bulk fluid. As a result, small anodes and cathodes may develop on the same metal surface, supporting localized corrosion. The biofilm also traps corrosive metabolites such as sulfides, organic acids and carbon dioxide near the metal surface, increasing the aggressiveness of the microenvironment [1,3].

Protection against MIC is difficult because the problem is dynamic. Microbial communities change with temperature, nutrient availability, flow velocity, water source, oxygen level, chemical treatment and seasonal conditions. A method that works in one system may fail in another. For example, the use of a biocide may reduce planktonic microorganisms in the water but leave sessile bacteria protected inside biofilms. Similarly, cathodic protection may reduce electrochemical corrosion but cannot be considered a universal solution if deposits, shielding and microbial communities are not controlled. This makes MIC management a field where laboratory knowledge must be adapted carefully to actual operating conditions.

Modern MIC protection is moving from single-method control to integrated risk management. The practical aim is to prevent microbial attachment, limit biofilm maturation, reduce corrosive metabolic activity, maintain protective barriers, monitor early warning indicators and respond before structural damage becomes critical. Such an approach is particularly important for carbon steel systems, buried pipelines, cooling circuits, marine installations and petroleum-related equipment, where water, nutrients and stagnant zones provide favorable conditions for microbial growth [3,4].

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The relevance of this topic is increasing as industry seeks longer service life, safer infrastructure and more sustainable chemical treatment. Excessive use of toxic biocides is no longer acceptable as the only control strategy. At the same time, untreated MIC can create serious environmental and economic consequences. Therefore, the current scientific and practical task is to develop balanced protection programs that combine engineering design, material science, microbiology, electrochemistry and environmental responsibility.

MATERIAL AND METHODS

This article was prepared as a narrative analytical review. The material included recent scientific publications on MIC mechanisms and prevention, technical recommendations from corrosion-focused professional organizations, and case-based studies describing MIC in pipelines, cooling-water systems and petrochemical equipment. Priority was given to peer-reviewed articles and technical documents that discuss protection strategies rather than only the biological description of microorganisms.

The analysis was organized around four questions. First, what conditions make engineering systems vulnerable to MIC? Second, which protective measures are commonly used in practice? Third, what are the limitations of each protective method? Fourth, how can these methods be combined into an integrated corrosion management plan? The selected literature was compared according to mechanism, protection method, monitoring approach and field applicability.

The methodological approach was interdisciplinary. Microbiological aspects were evaluated through biofilm formation, microbial metabolism and microbial community behavior. Chemical aspects were considered through pH, salinity, dissolved oxygen, sulfide production, nutrient availability and water chemistry. Engineering aspects were analyzed through material selection, surface condition, coating performance, flow regime, pigging, dead legs, weld zones, inspection access and maintenance procedures. This structure was chosen because MIC cannot be understood correctly if it is reduced to only bacteria or only metal corrosion.

The article does not present new laboratory experiments. Instead, it synthesizes available knowledge to formulate practical conclusions for prevention and protection. This is appropriate for a conference thesis or student scientific article because the main objective is to explain how MIC protection should be organized in industrial and technical systems. The results are therefore presented as a structured classification of protective approaches, expected benefits and common failure modes.

RESULTS

The review shows that MIC risk begins when three groups of factors meet: a susceptible material, a suitable environment and an active microbial community. Carbon steel is particularly vulnerable in many industrial systems because it is widely used and relatively inexpensive, but it can corrode rapidly under deposits and biofilms. Stainless steels and copper alloys may also suffer MIC under specific conditions, especially when passive films are locally damaged or when chloride-rich and stagnant environments promote pitting. Therefore, the first result is that MIC is not limited to one metal or one industry; it is a cross-sector problem affecting many materials and operating conditions [1,3].

The second result is that biofilm is the central structure in MIC development. Planktonic microorganisms floating in water are easier to reduce by chemical treatment, but sessile microorganisms attached to the surface are more difficult to eliminate. The extracellular polymeric matrix protects them from biocides, traps nutrients and creates microenvironments with different oxygen and ion concentrations. Consequently, a water sample showing low bacterial count does not always prove that the surface is safe. Surface-associated monitoring is more informative than only measuring microorganisms in the bulk fluid [4,8].

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The third result is that the most effective protection starts before the system is commissioned. Good design reduces stagnant zones, dead legs, crevices, rough welds and areas where deposits can accumulate. Smooth internal surfaces, correct drainage, controlled flow, accessible sampling points and compatibility between materials and water chemistry reduce the probability of biofilm establishment. Poor design cannot be fully corrected by later chemical treatment; it only becomes more expensive to manage. This is a critical practical point that is often underestimated during construction or modernization.

The fourth result concerns mechanical cleaning. Pigging, flushing, filtration and removal of sludge or scale are not secondary measures; they are essential parts of MIC control. Deposits protect microorganisms and create local chemical gradients. If deposits remain in the system, even strong biocide programs may fail because the active substance does not reach microorganisms at the metal surface. In pipelines, analysis of pigging returns can provide valuable information about solids, corrosion products and microbial activity. This makes cleaning both a mitigation method and a diagnostic tool [8].

The fifth result is that coatings and linings are useful but not self-sufficient. Epoxy, phenolic, polymeric and other lining systems can separate the metal from the corrosive environment. However, coating defects, holidays, mechanical damage, poor surface preparation, underfilm water transport and aging can create localized attack points. Once microorganisms colonize a defect, corrosion may become concentrated beneath the coating edge. Therefore, coating protection must include quality control during application, holiday testing, compatibility assessment, periodic inspection and repair of damaged areas.

The sixth result is that chemical control must be targeted and monitored. Oxidizing and non-oxidizing biocides, corrosion inhibitors, dispersants and biodispersants are commonly used in cooling-water systems and pipelines. Yet chemical treatment fails when dosage is insufficient, injection points are poorly selected, mixing is weak, biofilm is mature or microorganisms develop tolerance. Moreover, environmental and occupational safety concerns require rational use rather than indiscriminate chemical addition. The best chemical program is based on system-specific monitoring, not routine dosing without evidence.

The seventh result concerns cathodic protection. Cathodic protection is a powerful electrochemical method for buried and submerged structures, but its relation with MIC is complex. It can reduce metal dissolution by shifting the potential, yet shielding by deposits or disbonded coatings may reduce its effectiveness. In some environments, hydrogen evolution and changes in local chemistry may influence microbial processes. Therefore, cathodic protection should be considered as part of a broader corrosion control plan, not as a substitute for cleaning, coating maintenance and microbiological monitoring [2,4].

The eighth result is that monitoring must combine corrosion data and biological data. Useful tools include corrosion coupons, electrical resistance probes, linear polarization resistance, ultrasonic thickness measurements, inline inspection, non-destructive testing, water chemistry analysis, sulfide measurement, deposit analysis, culture-based methods, ATP testing and molecular microbiological methods. Each method has limitations. For instance, culture tests may miss viable but non-culturable microorganisms, while molecular methods can detect DNA from inactive cells. Therefore, decisions should rely on multiple indicators rather than a single test.

DISCUSSION

The central lesson from MIC research is that protection must be preventive and integrated. A weak plan treats MIC as a microbiology problem and responds only by adding biocide. That approach is incomplete. Microorganisms act within an electrochemical and engineering environment; therefore,

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protection must change that environment. The smallest effective strategy includes three blocks: reduce microbial attachment, maintain barriers between the environment and the metal, and monitor early signs of localized attack.

Material selection is the first defensive layer. Corrosion-resistant alloys, non-metallic materials, composite pipes, HDPE liners and internally coated steel systems may reduce MIC risk in selected applications. However, more expensive material does not automatically mean immunity. Stainless steel may pit under biofilms in chloride-containing environments, and polymers may have limits related to temperature, pressure, mechanical damage or chemical compatibility. Material selection should therefore be based on actual operating conditions, not only on general corrosion charts.

Design is the second layer. Dead legs, low-flow zones, horizontal sections that collect water, rough internal surfaces, poorly finished welds and inaccessible parts create ideal sites for microbial settlement. Once such zones exist, the operator is forced to fight a permanent structural weakness. For this reason, MIC prevention should be included in the design stage through drainability, cleanability, inspection access, flow control and avoidance of unnecessary crevices. Design for maintainability is cheaper than emergency repair after perforation.

Surface protection is the third layer. Coatings and linings can reduce metal exposure, but their success depends on surface preparation and application quality. In practice, coating failure often begins at defects. A small holiday can become an anode surrounded by a larger protected cathodic area, accelerating local attack. In MIC-prone systems, this risk is increased because microorganisms colonize defects and use the crevice-like environment as a stable habitat. Therefore, coating inspection should not be treated as a formality; it is a core part of MIC prevention.

Water and process chemistry control is the fourth layer. Microorganisms need water, nutrients and suitable physical conditions. Reducing unnecessary nutrient input, controlling pH, limiting stagnant water, managing dissolved oxygen, controlling sulfides and removing suspended solids can weaken biofilm development. In cooling systems, water reuse and concentration cycles may increase salt content and microbial nutrients, making monitoring more important. The treatment program should be adjusted to the chemical and biological behavior of the system rather than copied from another facility.

Biocides remain useful, but they are not magic. Their effect depends on concentration, contact time, penetration into biofilm, compatibility with other chemicals and system hydraulics. If microorganisms are hidden under thick deposits, a biocide may reduce planktonic counts while corrosion continues beneath the deposit. Alternating biocides, using biodispersants, cleaning before treatment and verifying surface effects can improve performance. At the same time, excessive chemical use may create environmental burden and cost without proportional benefit. The rational question is not how much biocide can be added, but whether the treatment reaches the actual corrosion site.

Mechanical control is often underestimated. Pigging, flushing and deposit removal directly attack the physical shelter of biofilms. In many cases, chemical treatment becomes effective only after deposits are removed. For pipelines, pigging data also reveal whether solids are accumulating and whether a treatment program is working. For tanks and cooling systems, scheduled cleaning prevents the formation of long-term microbial reservoirs. Therefore, mechanical maintenance should be planned, documented and connected to corrosion monitoring results.

Cathodic protection is essential for many buried and marine structures, but it should be managed carefully. Potential surveys, coating condition, soil or water resistivity, shielding and stray currents must be assessed. MIC can occur in small shielded regions where cathodic current does not reach adequately. This means that cathodic protection readings alone may not guarantee safety. A good program combines cathodic protection data with coating inspection, microbiological assessment and direct examination of suspicious locations.

Monitoring is the point where many MIC programs fail. A system may have a written corrosion plan, but if data are not interpreted together, early warning signals are missed. For example, an increase in iron, sulfide odor, black deposits, pH decrease, pigging debris, coupon pitting or localized wall thinning should trigger investigation. The absence of one indicator does not eliminate MIC risk. The strongest monitoring plan integrates microbiology, chemistry, electrochemistry and inspection. It also defines response thresholds before damage becomes severe.

A modern direction in MIC protection is the development of more environmentally acceptable methods. These include improved anti-biofilm coatings, enzyme-based biofilm disruption, biosurfactants, green corrosion inhibitors, nanostructured surfaces and smart sensors. These technologies are promising, but they should be evaluated critically. Laboratory success does not always translate into field performance because real systems contain mixed microbial communities, fluctuating chemistry, mechanical stress and aging surfaces. Therefore, new technologies should be introduced through pilot testing and risk-based validation.

The practical failure modes are clear. MIC protection fails when operators rely only on planktonic bacterial counts, ignore deposits, apply biocide without cleaning, install coatings without quality control, assume cathodic protection solves everything, select materials without considering local chemistry, or collect monitoring data without acting on it. These are not minor mistakes; they are the reason systems experience localized perforation despite having a nominal corrosion control program.

For educational and industrial practice, the topic should be taught as an interdisciplinary problem. Students and young specialists often learn microbiology, chemistry and materials science separately. MIC proves that real infrastructure problems do not respect disciplinary borders. A corrosion engineer must understand biofilms; a microbiologist must understand electrochemical cells; a maintenance specialist must understand sampling and inspection logic. Only such cooperation can make MIC protection reliable.

CONCLUSION

Protection against microbiologically influenced corrosion is one of the most important tasks in modern corrosion management. MIC is dangerous because it is localized, hidden, multidisciplinary and strongly dependent on real operating conditions. The presence of microorganisms alone is not enough to predict failure; the decisive factor is the interaction between microbial activity, biofilm structure, water chemistry, deposits, material properties and engineering design.

The most effective protection is integrated. It begins with correct material selection and design that reduces stagnant zones and deposit accumulation. It continues with high-quality coatings or linings, water chemistry management, mechanical cleaning, rational use of biocides, corrosion inhibitors, cathodic protection where appropriate, and continuous monitoring. No single method can be considered universal. Each method has limitations, and these limitations must be recognized before failure occurs.

The main preventive principle is simple: do not allow stable biofilms and deposits to create aggressive microenvironments on metal surfaces. Once mature biofilms and corrosion pits are established, control becomes more difficult and expensive. Therefore, proactive monitoring, early cleaning, correct chemical treatment and systematic inspection are more effective than late repair.

In conclusion, MIC protection should be organized as a risk-based management system rather than a one-time technical procedure. Facilities that combine microbiological diagnostics, corrosion monitoring and engineering maintenance have a much better chance of preventing leaks, shutdowns and structural failures. Future progress will depend on environmentally safer anti-biofilm technologies, better sensors and closer cooperation between materials scientists, microbiologists and engineers.

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