

# Investigation of the bactericidal-inhibitory effect of sulfonate- and benzalkonium chloride-based substance against corrosion caused by hydrogen sulfide (H<sub>2</sub>S), carbon dioxide (CO<sub>2</sub>), and microorganisms

Badanie działania bakteriobójczego i inhibującego substancji na bazie sulfonianu i chlorku benzalkoniowego, zapobiegającej korozji spowodowanej przez siarkowodór (H<sub>2</sub>S), dwutlenek węgla (CO<sub>2</sub>) oraz mikroorganizmy

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**ABSTRACT:** Corrosion in oilfield operations often occurs through complex synergistic mechanisms involving CO<sub>2</sub>, H<sub>2</sub>S, and microbologically influenced corrosion (MIC), necessitating multifunctional mitigation strategies. In this study, a new bactericidal corrosion inhibitor, designated SS-41ABAC, was synthesized under laboratory conditions by combining SS-41A and benzalkonium chloride (BAC) in a 4 : 1 ratio. The SS-41A inhibitor was synthesized based on sodium sulfonate and aminoethyl ethanolamine at room temperature for 1–2 hours. This formulation integrates the film-forming properties of the sulfonate-based inhibitor with the antimicrobial activity of benzalkonium chloride, resulting in a multifunctional inhibitor with both corrosion protection and bactericidal effects. Laboratory evaluations were conducted across a range of concentrations to assess protective performance against CO<sub>2</sub> and H<sub>2</sub>S corrosion using standardized electrochemical techniques. At 150 mg/L, SS-41ABAC achieved 98.3% inhibition efficiency against CO<sub>2</sub> corrosion and 96% against H<sub>2</sub>S corrosion. Microbiological assays demonstrated complete (100%) suppression of sulfate-reducing bacteria (SRB), iron-oxidizing bacteria (FeOB), and acid-producing bacteria (APB) at the same dosage. The dual-action efficacy, combined with favorable physicochemical characteristics, positions SS-41ABAC as a promising candidate for integrated corrosion management in oil and gas production systems, particularly under conditions where conventional single-function inhibitors are insufficient.

**Keywords:** iron-oxidizing bacteria, heterotrophic bacteria, acid producing bacteria, sodium sulfonate, aminoethyl ethanolamine, corrosion rate.

**STRESZCZENIE:** Korozja w eksploatacji pól naftowych często zachodzi w wyniku złożonych mechanizmów synergicznych związanych z obecnością CO<sub>2</sub>, H<sub>2</sub>S oraz korozją mikrobiologiczną (MIC), co wymaga zastosowania wielofunkcyjnych strategii ograniczających jej rozwój. W niniejszym badaniu zsyntetyzowano w warunkach laboratoryjnych nowy bakteriobójczy inhibitor korozji, oznaczony jako SS-41ABAC, poprzez połączenie SS-41A oraz chlorku benzalkoniowego (BAC) w proporcji 4 : 1. Inhibitor SS-41A został zsyntetyzowany na bazie sulfonianu sodu i aminoetyloetanoloaminy w temperaturze pokojowej przez 1–2 godziny. Preparat ten łączy właściwości tworzenia filmu ochronnego, charakterystyczne dla inhibitora na bazie sulfonianu z działaniem przeciwbakteryjnym chlorku benzalkoniowego, tworząc w ten sposób wielofunkcyjny inhibitor o działaniu zarówno antykorozyjnym, jak i bakteriobójczym. Przeprowadzono badania laboratoryjne w różnych stężeniach w celu oceny skuteczności ochrony przed korozją spowodowaną przez CO<sub>2</sub> i H<sub>2</sub>S, przy użyciu standardowych technik elektrochemicznych. Przy stężeniu 150 mg/L SS-41ABAC osiągnął 98,3% skuteczności inhibicji korozji wywołanej przez CO<sub>2</sub> oraz 96% w przypadku korozji wywołanej przez H<sub>2</sub>S. Testy mikrobiologiczne wykazały całkowite (100%) zahamowanie rozwoju bakterii redukujących siarczan (SRB), bakterii utleniających żelazo (FeOB) oraz bakterii wytwarzających kwas (APB) przy tej samej dawce. Podwójne działanie w połączeniu z korzystnymi właściwościami fizykochemicznymi czyni SS-41ABAC obiecującym kandydatem do zintegrowanego zarządzania korozją w systemach wydobywania ropy i gazu, szczególnie w warunkach, w których konwencjonalne inhibitory jednofunkcyjne okazują się niewystarczające.

**Słowa kluczowe:** bakterie utleniające żelazo, bakterie heterotroficzne, bakterie wytwarzające kwas, sulfonian sodu, aminoetyloetanoloamina, tempo korozji.

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## Introduction

Carbon steel, due to its mechanical properties and low cost, is widely used in industry. However, this material has low corrosion resistance, reducing the performance and useful life of engineering products. Therefore, it is necessary to apply methodologies that counteract the corrosion process, for instance, pre-treatments and the application of corrosion inhibitors. Among all inhibitors, the most important are the organic ones, also called adsorption inhibitors. Organic corrosion inhibitors are a class of molecules that delay or minimize the corrosive process. It has been shown that their effectiveness is mainly related to adsorption on the metal surface (Benhmamou et al., 2012), acting as a barrier layer and reducing the access of aggressive species (Rodríguez-Clemente et al., 2014). According to the literature, they usually adsorb onto the metal surface by displacing water molecules (Adeyemi, 2006), and the bonding efficiency is enhanced by the presence of polar functions with S, O or N atoms in the molecule, heterocyclic compounds and  $\pi$  electrons (Oguzie et al., 2004).

The serious consequences of the corrosion process have become a problem of worldwide significance. In addition to our everyday encounters with this form of degradation, corrosion causes plant shutdown, waste of valuable resources, loss or contamination of products, reduction in efficiency, costly maintenance, and expensive overdesign. It also jeopardizes safety and inhibits technological progress (Barton and Tomei, 1995).

Corrosion of metals and alloys results in significant economic losses worldwide. To control corrosion, large quantities of protective coatings such as paints, chemical inhibitors, and corrosion-resistant alloys are required. By understanding the underlying mechanisms of corrosion and the principles governing protection methods, countries can potentially reduce these losses by approximately 15–20%. Among various types of corrosion, microbiologically influenced corrosion (MIC) presents a major challenge, particularly in the oil and gas industry. Biological growth not only causes pollution but also accelerates corrosion processes. Numerous microorganisms have been shown to increase the rate of metal corrosion, often leading to localized corrosion rather than uniform degradation in affected environments (Stott, 1988; Yuan et al., 2012; Flores et al., 2013). Microbiologically influenced corrosion (MIC) is responsible for most internal corrosion found in oil, gas, and water transmission pipelines. Bacterial colonization on pipeline surfaces leads to the formation of complex microbial communities comprising multiple bacterial species that interact synergistically to sustain their growth. Among the bacteria known to contribute to corrosion are acid-producing bacteria (APB), sulfate-reducing bacteria (SRB), iron-oxidizing bacteria (FeOB), and manganese-oxidizing bacteria (MnOB). Of these, SRB and

APB are the predominant bacterial groups frequently detected in oil and gas pipelines. Sulfate-reducing bacteria generate hydrogen sulfide ( $H_2S$ ), whereas acid-producing bacteria produce organic acids such as acetic acid and inorganic acids such as sulfuric acid. Both metabolites are highly corrosive and play a critical role in the microbiologically influenced corrosion (MIC) of pipeline infrastructure.

Many other types of bacteria, such as manganese-oxidizing bacteria and heterotrophic bacteria, are also present. Iron-oxidizing bacteria precipitate the iron present in solution arising from corrosion and form a tubercle on the top of the corrosion pit. Microorganisms present in aqueous environment form biofilms on solid surfaces. Biofilm consists of populations of microorganisms and their hydrated polymeric secretions. Numerous types of organisms may exist in any particular biofilm, ranging from strictly aerobic bacteria at the water interface to anaerobic bacteria such as sulphate reducing bacteria (SRB) at the oxygen-depleted metal surface (Atlas et al., 1993; Gilbert et al., 2002; Chang et al., 2007; Sastri et al., 2012; Hussein et al., 2013; Turkiewicz et al., 2015). The formation of biofilms contributes to corrosion through three primary mechanisms: physical deposition, the generation of corrosive by-products, and depolarization of the corrosion cell via chemical reactions. To mitigate microbiologically influenced corrosion (MIC), various chemical agents known as bactericidal inhibitors are employed. The primary objective of this study is to evaluate the SS-41ABAC bactericidal inhibitor, formulated with sulfonates and quaternary ammonium compounds, and to investigate its performance under various aggressive environmental conditions for effective control of microbiologically influenced corrosion. In the oil industry, the key criterion for bactericidal corrosion inhibitors is their high protective efficacy. However, it is important to recognize that the technological properties of these reagents, while not solely determinative of their overall effectiveness, play a significant role in selecting an appropriate inhibitor. Given that application conditions can impose varying demands on the physicochemical and technological characteristics of chemical reagents, comprehensive analysis of these properties is essential for the informed development and selection of inhibitors in laboratory settings.

## Methodological part

A new bactericidal inhibitor named SS-41ABAC with a complex effect was synthesized by the authors in laboratory conditions based on SS-41A and benzalkonium chloride (BAC) (in a ratio of 4:1). The SS-41A inhibitor was synthesized based on sodium sulfonate and aminoethyl ethanolamine at room temperature for 1-2 hours. Benzalkonium chloride (BAC)

**Table 1.** Physicochemical properties of the SS-41ABAC inhibitor–biocide

**Tabela 1.** Właściwości fizykochemiczne inhibitora-biocydu SS-41ABAC

Property	Value	Test method
External appearance	Dark brown liquid	Visual inspection
Density at 20°C [g/cm <sup>3</sup> ]	0.935–0.958	GOST 3900-85
Freezing point [°C]	< –20	GOST 20287-91
Kinematic viscosity at 20°C [mm <sup>2</sup> /s]	45	GOST 33-2000
pH (3% aqueous solution)	9.0–10.0	pH-meter
Flash point [°C]	< 72	GOST 6356-75

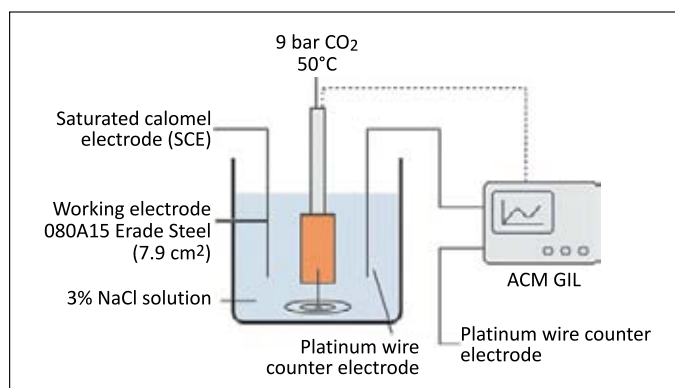
was used as a finished product. During laboratory studies, the physicochemical properties of the SS-41ABAC reagent were determined (Table 1), and the protective effect against CO<sub>2</sub>, hydrogen sulfide, and microbiological corrosion was investigated.

### Determination of the protective effect against CO<sub>2</sub> corrosion

The ACM GIL AC device is a high-specification corrosion monitoring instrument designed for various AC/DC corrosion tests. It includes a potentiostat, galvanostat, and zero resistance ammeter, making it suitable for comprehensive corrosion studies. In the study of corrosion protection abilities of sulfonates and their compositions, the device was utilized in conjunction with the Linear Polarization Resistance (LPR) method. This electrochemical technique allows direct measurement of corrosion rates in real time, providing valuable data for evaluating the effectiveness of corrosion inhibitors.

### Schematic diagram of the experimental setup for LPR tests

The experimental setup for the Linear Polarization Resistance (LPR) tests consisted of a three-electrode electrochemical cell connected to the ACM GIL AC corrosion monitoring device. The working electrode was made of 080A15 Erade Steel with a surface area of 7.9 cm<sup>2</sup>, carefully cleaned with acetone prior to use. A platinum wire served as the counter electrode, and a saturated calomel electrode (SCE) was used as the reference electrode. The cell contained a 3% sodium chloride (NaCl) solution, which was continuously stirred using a magnetic stirrer to ensure homogeneity. The solution was exposed to 9 bar CO<sub>2</sub> gas pressure at 50°C throughout the test duration. The ACM GIL device, equipped with potentiostat, galvanostat, and zero resistance ammeter functionalities, was used to apply the polarization signal and record the electrochemical responses. Data acquisition was managed via ACM version 5 software, which enabled real-time monitoring of corrosion potential and current density. This setup allowed precise measurement of corrosion rates under simulated CO<sub>2</sub>

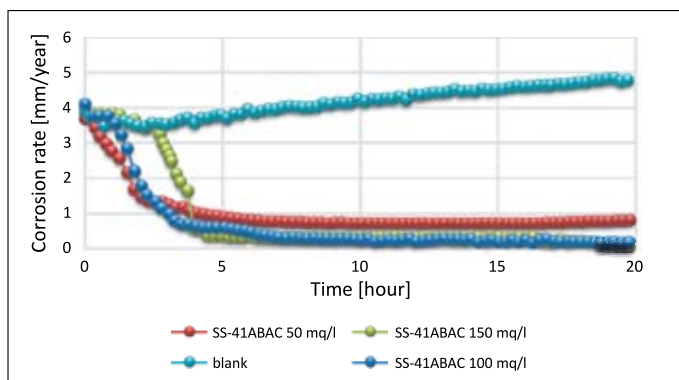


**Figure 1.** Schematic diagram of the experimental setup for LPR tests (created by the authors using BioRender)

**Rysunek 1.** Schematyczny rysunek układu eksperymentalnego do badań liniowej rezystancji polaryzacyjnej (rysunek stworzony przez autorów przy użyciu programu BioRender)

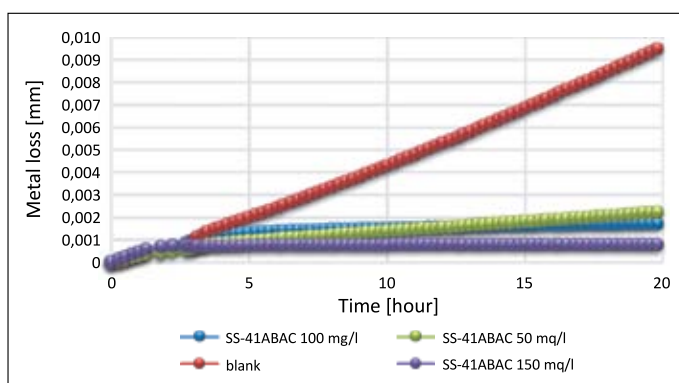
corrosion conditions, providing reliable evaluation of inhibitor performance. The software presented these results in graphical formats, including potential-current density, corrosion rate-time, and metal loss-time. The LPR method, as employed in this study, is ideal for plant monitoring, offering an almost instantaneous indication of corrosion rates (Figure 1).

The effect of the inhibitor on CO<sub>2</sub> corrosion was investigated at concentrations of 50, 100, and 150 mg/L. The detailed results are presented and analyzed in Figures 2 and 3, as well as Tables 2 to 5. Figures 2 and 3 illustrate the corrosion rate and metal loss trends over time at different inhibitor concentrations, clearly showing the inhibitory effect as concentration increases. Tables 2 to 5 provide comprehensive quantitative data, including Linear Polarization Resistance (LPR), corrosion current density (I<sub>corr</sub>), corrosion rate, and total metal loss for each tested condition. Table 2 shows the baseline corrosion parameters in the absence of inhibitor, while Tables 3, 4, and 5 present the corresponding data at 50, 100, and 150 mg/L inhibitor concentrations, respectively. These results collectively demonstrate a significant reduction in corrosion rate and metal loss with increasing inhibitor concentration, confirming the inhibitor's effectiveness against CO<sub>2</sub> corrosion under the tested conditions.



**Figure 2.** Corrosion rate progression over time under varying inhibitor concentrations

**Rysunek 2.** Zmiany tempa korozji w czasie przy różnych stężeniach inhibitorów



**Figure 3.** Change in metal loss over time at varying inhibitor concentrations

**Rysunek 3.** Zmiany w ubytku metalu w czasie przy różnych stężeniach inhibitora

**Table 2.** CO<sub>2</sub> corrosion measurement results in an environment without inhibitor: Time-dependent values of Linear Polarization Resistance (LPR), corrosion current density (I<sub>corr</sub>), corrosion rate, and total metal loss

**Tabela 2.** Wyniki pomiaru korozji CO<sub>2</sub> w środowisku bez inhibitora: wartości zależne od czasu liniowej rezystancji polaryzacyjnej (LPR), gęstości prądu korozyjnego (I<sub>corr</sub>), tempa korozji i całkowitego ubytku metalu

Time [hours]	LPR [ $\Omega \cdot \text{cm}^2$ ]	I <sub>corr</sub> [mA/cm <sup>2</sup> ]	Corrosion rate [mm/year]	Total metal loss [mm]
1.00	83.605	0.3120	3.6163	0.000401
3.00	85.977	0.3034	3.5165	0.001218
6.00	76.831	0.3395	3.9352	0.002524
9.00	74.033	0.3524	4.0839	0.003927
11.00	70.865	0.3681	4.2664	0.004909
13.00	68.245	0.3823	4.4303	0.005926
15.00	66.806	0.3905	4.5257	0.006977
17.00	65.296	0.3995	4.6304	0.008054
19.00	62.832	0.4152	4.8119	0.009176
20.00	63.294	0.4121	4.7768	0.009596

**Table 3.** CO<sub>2</sub> corrosion measurement results at an inhibitor concentration of 50 mg/L: Time-dependent values of Linear Polarization Resistance (LPR), corrosion current density (I<sub>corr</sub>), corrosion rate, and total metal loss

**Tabela 3.** Wyniki pomiaru korozji CO<sub>2</sub> przy stężeniu inhibitora wynoszącym 50 mg/l: wartości zależne od czasu liniowej rezystancji polaryzacyjnej (LPR), gęstości prądu korozyjnego (I<sub>corr</sub>), tempa korozji i całkowitego ubytku metalu

Time [hours]	LPR [ $\Omega \cdot \text{cm}^2$ ]	I <sub>corr</sub> [mA/cm <sup>2</sup> ]	Corrosion rate [mm/year]	Total metal loss [mm]
1.00	120.17	0.2171	2.7600	0.000292
3.00	242.85	0.1074	1.2449	0.000699
6.00	375.04	0.0696	0.8062	0.001034
9.00	413.34	0.0631	0.7315	0.001299
11.00	418.87	0.0623	0.7218	0.001469
13.00	425.43	0.0613	0.7107	0.001637
15.00	425.12	0.0614	0.7112	0.001804
17.00	410.37	0.0636	0.7368	0.001972
19.00	388.23	0.0672	0.7788	0.002150
20.00	375.66	0.0694	0.8048	0.002220

**Table 4.** CO<sub>2</sub> corrosion measurement results at an inhibitor concentration of 100 mg/L: Time-dependent values of Linear Polarization Resistance (LPR), corrosion current density (I<sub>corr</sub>), corrosion rate, and total metal loss

**Tabela 4.** Wyniki pomiaru korozji CO<sub>2</sub> przy stężeniu inhibitora wynoszącym 100 mg/l: wartości zależne od czasu liniowej rezystancji polaryzacyjnej (LPR), gęstości prądu korozyjnego (I<sub>corr</sub>), tempa korozji i całkowitego ubytku metalu

Time [hours]	LPR [ $\Omega \cdot \text{cm}^2$ ]	I <sub>corr</sub> [mA/cm <sup>2</sup> ]	Corrosion rate [mm/year]	Total metal loss [mm]
1.00	80.588	0.3237	3.53	0.000448
3.00	4324.500	0.0060	0.97	0.001012
6.00	8788.900	0.0030	0.46	0.001374
9.00	10141.000	0.0026	0.26	0.001484
11.00	10531.000	0.0025	0.24	0.001533
13.00	10709.000	0.0024	0.27	0.001577
15.00	11774.000	0.0022	0.18	0.001619
17.00	11753.000	0.0022	0.20	0.001660
19.00	12589.000	0.0021	0.19	0.001701
20.00	12236.000	0.0021	0.18	0.001716

As illustrated in the figures and detailed in the tables, the protective effect of the inhibitor increased with concentration, reaching its maximum efficacy at 150 mg/L. Specifically, the corrosion rate in the uninhibited environment was measured at approximately 4.77 mm/year after 20 hours of exposure. In contrast, the presence of the inhibitor at 150 mg/L reduced the corrosion rate drastically to 0.08 mm/year over the same period. This substantial decrease corresponds to a corrosion

**Table 5.** CO<sub>2</sub> corrosion measurement results at an inhibitor concentration of 150 mg/L: Time-dependent values of Linear Polarization Resistance (LPR), corrosion current density (I<sub>corr</sub>), corrosion rate, and total metal loss

**Tabela 5.** Wyniki pomiaru korozji CO<sub>2</sub> przy stężeniu inhibitora wynoszącym 150 mg/l: wartości zależne od czasu liniowej rezystancji polaryzacyjnej (LPR), gęstości prądu korozyjnego (I<sub>corr</sub>), tempa korozji i całkowitego ubytku metalu

Time [hours]	LPR [ $\Omega \cdot \text{cm}^2$ ]	I <sub>corr</sub> [mA/cm <sup>2</sup> ]	Corrosion rate [mm/year]	Total metal loss [mm]
1.00	78.991	0.3303	3.8276	0.000477
3.00	167.860	0.1554	2.6400	0.000728
6.00	615.360	0.0424	0.3600	0.000744
9.00	1314.200	0.0198	0.3100	0.000756
11.00	1539.100	0.0169	0.3100	0.000763
13.00	1701.600	0.0153	0.3300	0.000770
15.00	1714.900	0.0152	0.3100	0.000776
17.00	1727.400	0.0151	0.2100	0.000783
19.00	1725.600	0.0151	0.1000	0.000788
20.00	1790.400	0.0146	0.0800	0.000791

inhibition efficiency of 98.3%, indicating a highly effective barrier against CO<sub>2</sub>-induced metal degradation. The data also show consistent trends across other measured parameters, such as corrosion current density and total metal loss, further validating the inhibitor’s capability to significantly mitigate corrosion processes. These results confirm that the inhibitor provides robust protection by effectively reducing the electrochemical activity responsible for metal dissolution, making it a promising candidate for industrial applications requiring CO<sub>2</sub> corrosion control.

**Determination of the protective effect against H<sub>2</sub>S corrosion (Weight Loss Measurement)**

The protective effect of the SS-41ABAC inhibitor against H<sub>2</sub>S corrosion was studied by the gravimetric method in accordance with GOST-9.506-87. The tests were carried out for 6 hours in a U-shaped tube equipped with a mechanical stirrer operating at 500 rpm. SS-41ABAC corrosion inhibition tests were performed using mild steel specimens. These specimens were washed with distilled water and degreased with absolute ethanol. The specimens were dried and kept in a desiccator. The weight loss was determined at different immersion times by weighing the cleaned samples before and after soaking the specimens in 1000 cm<sup>3</sup> of the corrosive solution, namely 1% NaCl saturated with H<sub>2</sub>S in a closed beaker with stirring, in the absence and presence of various concentrations of the investigated inhibitor. Triplicate specimens were exposed to each condition, and the mean weight loss was reported. The corrosion rate (CR) (Benhmamou et al., 2012), inhibition effi-

ciency (Rodríguez et al., 2014), and surface coverage (Adeyemi 2006) were calculated using the following equation:

$$CR = (Wb - Wa) / S \cdot t$$

where:

CR – corrosion rate,

Wb and Wa – sample weight measured before and after soaking in the corrosive solution,

S – exposed area,

t – time in hours.

Inhibitor efficiency ( $\eta$  in %) is calculated using the following equation:

$$\eta(\%) = CR(\text{blank}) - CR(\text{Inh}) / CR(\text{blank}) \cdot 100\%$$

where CR(blank) and CR(Inh) indicate the corrosion rate in the absence and presence of the inhibitor in the corrosive solution.

Table 6 summarizes the results of corrosion inhibition studies conducted at varying concentrations of the SS-41ABAC inhibitor-bactericide. The data clearly demonstrate a concentration-dependent improvement in corrosion protection, with the inhibitor exhibiting its highest efficacy at 150 mg/L. At this concentration, the inhibitor achieved a maximum protection effect of 96%, indicating a significant reduction in corrosion rate compared to the uninhibited environment. This is reflected in the notable decrease in reagent consumption, metal loss, and corrosion rate values. Additionally, the delay factor at 150 mg/L reached 25.72, underscoring the inhibitor’s strong capacity to slow down the corrosion process. These results confirm the high performance of the inhibitor at elevated concentrations and suggest its practical potential for effective corrosion mitigation in industrial applications.

Such behavior is well-supported by established corrosion science, where it is understood that increasing inhibitor concentration enhances the formation of a stable and adherent protective film on the metal surface. This film acts as a physical barrier, reducing the contact between the corrosive agents and the metal substrate, thereby limiting electrochemical reactions that cause corrosion. The inhibitor molecules typically adsorb onto the metal surface through physical or chemical interactions, blocking active corrosion sites and decreasing metal dissolution. Consequently, higher concentrations of inhibitor result in greater surface coverage and improved corrosion resistance, consistent with the trends observed in this study. These mechanisms explain the significant increase in protection efficiency and delay factor observed at 150 mg/L, highlighting the inhibitor’s effectiveness for corrosion control in industrial applications.

**Determination of biocide activity**

It is well known that sessile bacteria accelerate corrosion processes in several ways. Sulfate-reducing bacteria (SRB)

**Table 6.** Protective effect of the SS-41ABAC inhibitor-bactericide on metal corrosion: reagent concentration, metal loss, corrosion rate, delay factor, and protection efficiency at various concentrations

**Tabela 6.** Ochronne działanie inhibitora-bakteriocydu SS-41ABAC na korozję metali: stężenie odczynnika, ubytek metalu, tempo korozji, współczynnik opóźnienia i skuteczność ochrony przy różnych stężeniach

Reagent concentration [mg/L]	Metal loss [g]	Corrosion rate [g/m <sup>2</sup> · h]	Delay factor	Protection effect [%]
Without inhibitor	0.01210	1.2870	–	–
SS-41ABAC 50 mg/L	0.00410	0.4901	2.63	62
SS-41ABAC 100 mg/L	0.00100	0.1402	9.90	89
SS-41ABAC 150 mg/L	0.00030	0.0511	25.72	96

produce hydrogen sulfide (H<sub>2</sub>S) as a metabolic by-product, which significantly increases the corrosiveness of brine environments. The presence of H<sub>2</sub>S promotes the formation of iron sulfide compounds on metal surfaces, leading to localized corrosion such as pitting and stress corrosion cracking. This microbial activity not only accelerates metal degradation but also causes mechanical damage manifested as cracking and blistering, severely compromising the integrity of pipelines and equipment.

Acid-producing bacteria (APB), on the other hand, generate organic and inorganic acids during their metabolic processes. These acids actively dissolve and remove the protective passivating oxide films that normally shield metal surfaces from aggressive environments. Without this oxide layer, the underlying metal becomes exposed to corrosive agents, facilitating uniform and localized corrosion. Furthermore, the acidic conditions created by APB can lower the pH of the surrounding environment, exacerbating the corrosion rate. From a biological perspective, these microorganisms form biofilms on metal surfaces, creating microenvironments that differ chemically and physically from the bulk fluid. Within these biofilms, gradients of pH, oxygen, and metabolites develop, promoting differential aeration and concentration cells that intensify corrosion processes. The synergistic action of SRB and APB within these biofilms leads to microbially influenced corrosion (MIC), a complex phenomenon that is often more aggressive than abiotic corrosion due to the continuous regeneration of corrosive metabolites and the protective niche biofilms provide to microbial communities. The quantification of microorganisms was performed in accordance with NACE Standard TM0194-2014. Different culture media selectively promote the growth of bacteria capable of utilizing the specific nutrients provided. Sulfate-reducing bacteria (SRB) were cultured using Postgate's Medium B. Iron-oxidizing bacteria were cultured in a medium prepared in accordance with the formulation of the NACE Standard TM0194-2014.

The medium composition per 1000 mL of distilled water was as follows: CaCl<sub>2</sub> · 6H<sub>2</sub>O (0.2 g), KH<sub>2</sub>PO<sub>4</sub> (0.5 g), ammonium nitrate (NH<sub>4</sub>NO<sub>3</sub>) (0.5 g), ferric ammonium citrate

[Fe(NH<sub>4</sub>)<sub>5</sub>(C<sub>6</sub>H<sub>5</sub>O<sub>7</sub>)] (6.0 g), NaCl (optional), MgSO<sub>4</sub> · 7H<sub>2</sub>O (0.5 g), and NaNO<sub>3</sub> (0.5 g). To assess the presence of general heterotrophic bacteria (GHB), which include both aerobic and facultative anaerobic bacteria, heterotrophic bacteria media and/or phenol red dextrose broth or standard nutrient broth were employed. Phenol red dextrose broth vials that become turbid within 1 to 14 days are considered positive for general heterotrophic bacterial growth. Additionally, vials exhibiting a color change from red to yellow (or white) are scored as positive for acid-producing bacteria. This approach enables targeted detection and monitoring of microbial populations relevant to corrosion and biofouling in industrial systems. In the serial dilution method for bacterial culturing, progressively smaller aliquots of the original sample are transferred sequentially into a series of dilution vials. This stepwise reduction in concentration helps isolate and quantify viable bacteria by reducing microbial density, facilitating the growth of discrete colonies that can be more easily counted and analyzed. This is accomplished by a stepwise 1:10 dilution scheme until, in theory, no bacteria are transferred. The growth medium in the serial dilution vials provides nutrients for prolific growth of the transferred bacteria. A growing bacterial population causes a visible change in the respective vial. For example, turbidity (cloudiness) in general count heterotrophic vials, a color change from red to yellow in phenol red vials, and a black precipitate in sulfate-reducer vials. The final vial of dilution series to show these conditions should be the vial that received between 1 and 10 bacteria and represents the dilution factor necessary to reduce the original inoculum to these concentrations. The incubation temperature for bacterial cultures was maintained within ±5°C of the water temperature measured at the time of sample collection and was recorded for each test. Cultures were monitored over a 28-day period. Vials that developed a black precipitate were recorded as positive; however, blackening observed within 2 hours after inoculation was not considered a positive result, as it was attributed to sulfides present in the original water sample. Bacterial numbers were estimated using the serial dilution method in accordance with NACE Standard TM0194-2014. This approach follows the principle of the most

probable number (MPN), where serial dilutions are used to statistically estimate the concentration of viable microorganisms in the sample. The original water sample was heavily contaminated with bacteria because it was taken from produced water. This water represents an aggressive environment that supports the proliferation of various microbial populations, resulting in high bacterial counts.

The percentage of bacterial growth inhibition ( $Z$ ) was calculated using the following equation:

$$Z = [(\log n_0 - \log (n_{i.g}) / \log n_0) \cdot 100\%$$

where:

$n_0$  – number of bacteria (cells/mL) in the reagent-free control medium,

$n_{i.g}$  – number of bacteria (cells/mL) in the reagent-containing medium,

$Z$  – bactericidal activity [% growth inhibition].

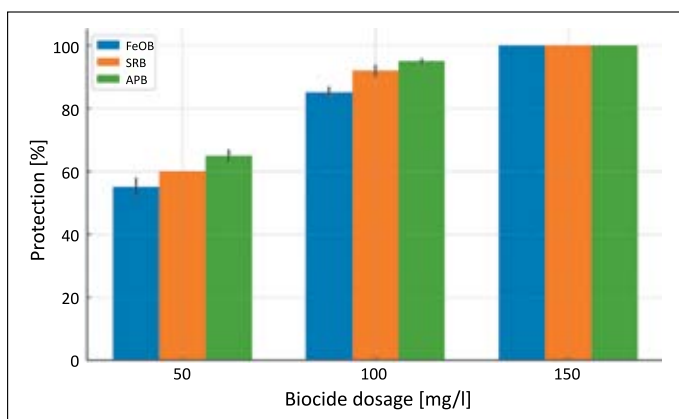
By multiplying the number of colonies observed in a given dilution by the corresponding dilution factor, an estimate of the bacterial concentration per milliliter in the original sample can be obtained. In this study, the initial bacterial counts in the water sample were approximately  $10^6$  cells/mL for sulfate-reducing bacteria (SRB),  $10^6$  cells/mL for iron-oxidizing bacteria (FeOB), and  $10^5$  cells/mL for acid-producing bacteria (APB). Following the application of the biocide treatment to the water, a significant reduction in bacterial populations was observed. The resulting bacterial counts and the effectiveness of the biocide are illustrated in Figure 4, which demonstrates the biocide's impact on controlling microbial growth within the system.

The biocidal efficacy of the SS-41ABAC reagent was evaluated against three major types of corrosion-inducing bacteria: iron-oxidizing bacteria (FeOB), sulfate-reducing bacteria (SRB), and acid-producing bacteria (APB) at varying concentrations. At the lowest concentration tested (50 mg/L),

inhibition efficiencies were moderate, with 55% for FeOB, 60% for SRB, and 65% for APB. Upon increasing the dosage to 100 mg/L, the inhibitory effects improved significantly, achieving 85% inhibition for FeOB, 93% for SRB, and 95% for APB. At the highest concentration tested (150 mg/L), complete inhibition (100%) of all three bacterial groups was observed. As the biocide dosage increased, a corresponding enhancement in bacterial inhibition rates was observed, demonstrating a clear dose-dependent effect. This trend is consistent with recent findings in the literature, where biocidal agents such as cetylpyridinium chloride have been shown to effectively mitigate SRB-induced corrosion in simulated oil-field conditions (Hu et al., 2025). Specifically, Hu et al. (2025) reported significant inhibition of SRB activity on copper surfaces, highlighting the critical role of quaternary ammonium compounds in disrupting bacterial metabolism and biofilm formation. Similarly, Chen et al. (2024) demonstrated that sulfate-reducing bacteria, such as *Desulfovibrio desulfuricans*, accelerate microbiologically influenced corrosion (MIC) of copper, emphasizing the importance of strong biocides for corrosion control in industrial settings. Furthermore, Yadav et al. (2024) investigated the effect of cetylpyridinium chloride on corrosion inhibition of mild steel in acidic environments, confirming that increased biocide concentrations correlate with improved corrosion protection through bacterial suppression. Environmental factors such as pH and temperature also significantly affect the activity of sulfate-reducing bacteria and the efficacy of inhibitors, as shown by Moloantoa et al. (2023), who modeled these effects in stirred bioreactors, further underscoring the complexity of MIC control. The results obtained with SS-41ABAC align well with these studies, reinforcing its potential as an effective multifunctional inhibitor against corrosion-inducing bacteria under varying operational conditions. These results indicate that SS-41ABAC exhibits strong dose-dependent antimicrobial activity, effectively suppressing bacterial populations responsible for microbiologically influenced corrosion, and demonstrating its potential as an effective biocide in corrosion control applications.

## Conclusion

A new multifunctional corrosion inhibitor called SS-41ABAC has been developed. The composition of this inhibitor mainly consists of the sodium salt of sulfonic acid obtained from the sulfation of aminoethylethanolamine, benzalkonium chloride, and an organic solvent. The main goal in the creation of this inhibitor is to provide a comprehensive approach to combating various types of corrosion. The effect of the developed composition-type inhibitor against CO<sub>2</sub> corrosion



**Figure 4.** Antimicrobial activity of SS-41ABAC reagent against different types of bacteria

**Rysunek 4.** Działanie przeciwbakteryjne odczynnika SS-41ABAC wobec różnych rodzajów bakterii

has been studied at various concentrations using an ACM GILL AC potentiometer for 20 hours. It was determined that at a concentration of 150 mg/L, the inhibitor's protective effect was 98.3%. At the same concentration, the protection against H<sub>2</sub>S corrosion was studied gravimetrically over a period of 6 hours, and it was found that the protective effect of the reagent was 96% at a concentration of 150 mg/L. The biocidal effect of SS-41ABAC inhibitor against various types of corrosion-inducing bacteria has been studied at different concentrations. It was determined that at a concentration of 150 mg/L, the reagent exhibited a 100% protective effect against all three types of bacteria (SRB, FeOB, APB).

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### Legislative acts and normative documents

- NACE Standard TM0194-2014 Field monitoring of bacterial growth in oil and gas systems. American National Standards Institute.



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