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## Original article

# Study of the sulfidogenic bacteria activity in the formation microflora of an oil field (Kazakhstan) and their potential contribution to corrosion processes

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## ABSTRACT

**Background:** Today at the oil field «N» there is an intensification of corrosion complications. Repeated monitoring of corrosion factors at all sites of the field has shown the localization of aggressive gases at site B, where thermal oil displacement technology is used, which could have triggered an increase in corrosion processes. In addition, large-scale studies of the microbial community of formation waters were conducted at field N, revealing the presence of sulfate-reducing and fermentative sulfidogenic bacteria, which could also contribute to the development of an aggressive environment. In this regard, the issue of the influence of the microbial community on corrosion processes remains a pressing task, and studies were conducted to identify the contribution of sulfidogenic bacteria to the formation of a corrosion-aggressive environment at this field.

**Aim:** To study the contribution of sulfidogenic bacteria of production waters to the formation of aggressive environments and corrosion at the N field.

**Materials and methods:** The objects of the study were samples of water extracted from group installations, wastewater from block cluster pumping stations, and vertical steel tanks. The studies were conducted using classical microbiological methods: anaerobic cultivation of bacteria, sowing using the tenfold dilution method, obtaining biofouling of the object under study in a natural environment, etc. A titrimetric method was used to determine the content of hydrogen sulfide and carbon dioxide. The dissolved oxygen content was determined by an express method using a Fibox 4 PreSens (Germany) fiber optic oxygen analyzer. The amount of mechanical impurities was determined by filtration followed by gravimetric analysis. The corrosion rate of steel coupons was determined gravimetrically by the loss of sample mass during their exposure at field facilities.

**Results:** All studied objects showed high content of planktonic ( $10^5$ – $10^8$  cells/ml) and adherent ( $10^6$ – $10^8$  cells/ml) sulfidogenic bacteria. The productivity of different physiological groups of sulfidogenic bacteria was determined: sulfate-reducing bacteria contribute most to hydrogen sulfide formation (125.6–762.5 mg/L), while sulfur-reducing bacteria contribute least (59.6–298.2 mg/L). Site B of the field, where development is carried out using thermal technology, is characterized by the highest corrosion potential. At the same time, the number of sulfidogenic bacteria at site B is comparable to their number at other sites of the field.

**Conclusion:** The microflora of the production waters of the N deposit has a high corrosion potential, but the greatest contribution to the formation of an aggressive environment is due to the use of thermal oil recovery technology at the deposit.

**Keywords:** hydrogen sulfide; carbon dioxide; sulfate-reducing bacteria; sulfidogenic bacteria; corrosion rate; aggressive gases.

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## Оригинальное исследование

# Исследование активности сульфидогенных бактерий пластовой микрофлоры нефтяного месторождения (Казахстан) и их потенциального вклада в коррозионные процессы

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## АННОТАЦИЯ

**Обоснование.** На сегодняшний день на нефтяном месторождении N наблюдается интенсификация коррозионных осложнений. Проведение неоднократного мониторинга коррозионных факторов на всех площадках месторождения показало локализацию агрессивных газов на площадке В, где применяется термическая технология нефтевытеснения, что могло спровоцировать усиление коррозионных процессов. Кроме того, на месторождении N были проведены масштабные исследования микробного сообщества пластовых вод, выявившие наличие сульфатовосстанавливающих, а также броодильных сульфидогенных бактерий, которые также могли способствовать развитию агрессивной среды. В связи с этим вопрос влияния микробного сообщества на процессы развития коррозии остаётся актуальной задачей, в связи с чем были проведены исследования, направленные на выявление вклада сульфидогенных бактерий в формирование коррозионно-агрессивной среды на данном месторождении.

**Цель.** Исследовать вклад сульфидогенных бактерий промышленных вод в процессы формирования агрессивной среды и коррозии на месторождении N.

**Материалы и методы.** Объектами исследования были пробы попутно-добываемых вод групповых установок, сточных вод блочных кустовых насосных станций и вертикальных стальных резервуаров. Исследования проведены с применением классических методов микробиологии: анаэробное культивирование бактерий, посевы методом предельных десятикратных разведений, получение биообрастаний исследуемого объекта в естественной среде и пр. Для определения содержания сероводорода и углекислого газа применяли титриметрический метод. Содержание растворённого кислорода определяли экспресс-методом на оптоволоконном анализаторе кислорода Fibox 4 PreSens (Германия). Количество механических примесей определяли методом фильтрации с последующим гравиметрическим анализом. Скорость коррозии стальных купонов определяли гравиметрическим по потере массы образцов за период их экспозиции на промысловых объектах.

**Результаты.** Во всех исследованных объектах выявлено высокое содержание планктонных ( $10^5$ – $10^8$  кл/мл) и адгезированных ( $10^6$ – $10^8$  кл/мл) сульфидогенных бактерий. Определена продуктивность разных физиологических групп сульфидогенных бактерий: наибольший вклад в образование сероводорода вносит сульфатовосстанавливающие бактерии (125,6–762,5 мг/л), наименьший – серовосстанавливающие бактерии (59,6–298,2 мг/л). Площадка В месторождения, где разработка ведётся с применением термической технологии, характеризуется наиболее высоким коррозионным потенциалом. При этом численность сульфидогенных бактерий на площадке В сопоставима с их численностью на других площадках месторождения.

**Заключение.** Микрофлора промысловых вод месторождения N обладает высоким коррозионным потенциалом, однако наибольший вклад в формирование агрессивной среды происходит по причине применения на месторождении термической технологии нефтеотдачи.

**Ключевые слова:** сероводород, углекислый газ, сульфатовосстанавливающие бактерии, сульфидогенные бактерии, скорость коррозии, агрессивные газы.

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## Түпнұсқа зерттеу

# Қазақстан мұнай кен орнының қабат микрофлорасының сульфидогендік бактерияларының белсенділігін және олардың коррозиялық процестерге әлеуетті үлесін зерттеу

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## АННОТАЦИЯ

**Негіздеу.** Бүгінгі таңда N мұнай кен орнында коррозиялық асқинулардың қарқыны байқалады. Кен орнының барлық аяндарында коррозиялық факторларға бірнеше рет мониторинг жүргізу коррозиялық процестердің күшеюіне түрткі болуы мүмкін мұнай ығыстырудың термиялық технологиясы қолданылатын B алаңында агрессивті газдардың оқшаулануын көрсетті. Бұдан басқа N кен орнында сульфатты қалпына келтіретін, сондай-ақ агрессивті ортаның дамуына ықпал етуі мүмкін ашыту сульфидогенді бактериялардың болуын анықтайтын қабат суларының микробтық қауымдастығына ауқымды зерттеулер жүргізілді. Осыған байланысты микробтық қауымдастықтың коррозияның даму процестеріне әсері мәселесі өзекті мәселе болып қала береді, сондықтан сульфидогендік бактериялардың осы кен орнында коррозиялық-агрессивті ортаны қалыптастыруға қосқан үлесін анықтауға бағытталған зерттеулер жүргізілді.

**Мақсаты.** Өнеркәсіптік сулардың сульфидогендік бактерияларының N кен орнында агрессивті орта мен коррозия қалыптастыру процестеріне қосқан үлесін зерттеу.

**Материалдар мен әдістер.** Зерттеу объектілері топтық қондырғылардың ілеспе өндірілетін суларының, блоқты бұталы сорғы станцияларының ағынды суларының және тік болат резервуарларының сынамалары болды. Зерттеулер микробиологияның классикалық әдістерін қолдана отырып жүргізілді: бактерияларды анаэробты өсіру, шекті он есе сұйылту әдісімен себу, табиғи ортада зерттелетін объектінің биологиялық ластануын алу және т. б. Күкіртсутек пен көмірқышқыл газының құрамын анықтау үшін титриметриялық әдіс қолданылды. Еріген оттегінің құрамы Fibox 4 PreSens (Германия) талшықты-оптикалық оттегі анализаторында жедел әдіспен анықталды. Механикалық қоспалардың саны сүзу әдісімен, содан кейін гравиметриялық талдаумен анықталды. Болат купондардың коррозия жылдамдығы коммерциялық объектілерде экспозиция кезеңінде үлгілердің массасын жоғалту арқылы гравиметриялық түрде анықталды.

**Нәтижелері.** Барлық зерттелген объектілерді планктонды ( $10^5$ – $10^8$  кл/мл) және адгезияланған ( $10^6$ – $10^8$  кл/мл) сульфидогендік бактериялардың жоғары мөлшері анықталды. Сульфидогендік бактериялардың әртүрлі физиологиялық топтарының өнімділігі анықталды: күкіртсутектің пайда болуына ең үлкен үлес сульфатты қалпына келтіретін бактериялар ( $125,6$ – $762,5$  мг/л), ең кішісі күкіртті қалпына келтіретін бактериялар ( $59,6$ – $298,2$  мг/л). Игеру термиялық технологияны қолдана отырып жүргізілетін кен орындарындағы B алаңы ең жоғары коррозиялық әлеуетпен сипатталады. Бұл ретте B алаңындағы сульфидогендік бактериялардың саны кен орнының басқа алаңдарындағы олардың санымен салыстырылады.

**Қорытынды.** N кен орнының кәсіпшілік суларының микрофлорасы жоғары коррозиялық потенциалға ие, алайда агрессивті ортаның қалыптасуына ең үлкен үлес кен орнында мұнай берудің термиялық технологиясын қолдану себебінен болады.

**Негізгі сөздер:** күкіртсутек, көмірқышқыл газы, сульфатты қалпына келтіруші бактериялар, сульфидогендік бактериялар, коррозия жылдамдығы, агрессивті газдар.

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## Introduction

Currently, the field N (Kazakhstan) is under commercial development. The viscous and resinous oil of this field is characterized by a significant sulfur content and a high concentration of high-molecular-weight compounds.

At the initial stage of field development, a low content of aggressive gases in the composition of reservoir fluids was observed: hydrogen sulfide was absent, while carbon dioxide was detected in small concentrations. Currently, the field is being operated using thermal recovery technology in combination with produced water injection. The application of thermal methods has ensured high rates of oil reserves recovery. During the long-term operation of the field using various technologies, a positive trend in the content of corrosive gases – hydrogen sulfide and carbon dioxide – has been observed, which has contributed to the intensification of corrosion processes.

Another reason for the increase in the content of hydrogen sulfide and carbon dioxide may be the metabolic activity of reservoir microflora [1], which in the system “reservoir – well – equipment” provokes, both directly and indirectly, a number of problems during oil production: corrosion cracking of metal equipment, reduction in well injectivity, deterioration of filtration properties, changes in oil quality, a decrease in oil recovery due to reservoir plugging by the accumulation of bacterial biofilms, as well as a decrease in the pH of the produced fluids.

Using high-throughput sequencing of the V3–V4 region of the 16S rRNA gene, sulfate-reducing bacteria such as *Desulfovibrio*, *Desulfomicrobium*, *Thermodesulfobacterium*, *Thermodesulfobacterium*, *Desulfotomaculum*, and other genera were detected in oil fields. Fermentative bacteria included representatives of the thermotogales genera *Thermosipho*, *Kosmotoga*, *Petrotoga*, *Deltaproteobacteria* of the genus *Pelobacter*, and bacteria of the genus *Thermicanus* from the order Bacillales. Syntrophic bacteria were represented by anaerobic bacteria of the genus *Thermovirga*. Sulfur-cycle bacteria also included representatives of the genera *Sulfurospirillum*, *Sulfurimonas*, *Brockia*, and others [2].

Sulfidogenic bacteria include fermentative bacteria and sulfate-reducing bacteria (hereinafter – SRB), which utilize oxidized sulfur compounds ( $S^0$ ,  $SO_4^{2-}$ ,  $SO_3^{2-}$ ,  $S_2O_3^{2-}$ , etc.) and produce hydrogen sulfide, as well as carbon dioxide, as the end products of their metabolism.

Fermentative bacteria possess a highly flexible metabolism and can inhabit various ecological niches, predominantly anaerobic, although they may also occur in microaerophilic and aerobic environments. Their habitats can be characterized by a wide range of temperatures (20–105°C) and pH values from 4.0 to 8.5.

Sulfidogenic bacteria – SRB, thiosulfates (hereinafter – TSB), and elemental sulfur (hereinafter –  $S^0$ RB) – play a key role in the oil production industry, as they are a potential source of various complications, one of which is corrosion.

In direct corrosive interactions with metals, bacteria utilize iron for their energy metabolism, thereby contributing to the gradual degradation of the metal. In indirect corrosive interactions, metal is degraded by the metabolic products of bacteria ( $H_2S$ ,  $CO_2$ , acids, enzymes, etc.), which are released both into the surrounding environment (produced waters) by all members of the sulfidogenic community and directly onto the metal surface by adherent cells [3].

To date, the microflora of the produced waters of the field and its contribution to the development of complications have been insufficiently studied and remain a relevant issue. The present work is aimed at investigating the potential contribution of the microbial community to corrosion processes at the facilities of the studied field.

## Materials and Methods

It is known that the microflora of produced waters comprises both planktonic and adherent bacteria, and the dominance of either form depends on various factors. In the present study, the bacterial community density at the facilities of the investigated field, microbial activity, and the contribution of bacteria to the accumulation of corrosive agents at the studied sites were examined.

Planktonic sulfidogenic bacteria were determined using the method of serial tenfold dilutions followed by inoculation onto selective nutrient media. The amount of hydrogen sulfide produced by the bacteria was assessed titrimetrically through the precipitation of sulfide ions as cadmium sulfide, followed by titration.

Adherent bacteria were studied using coupons installed at the field facilities; biofilm was scraped from the surface of the coupons, and the cells were enumerated by the serial dilution method.

The corrosion rate was assessed on the same coupons after removal of corrosion deposits, using the gravimetric method based on mass loss.

The chemical analysis of the water included:

- determination of  $CO_2$  by the titrimetric method using sodium hydroxide until a pH of 8.4 was reached;
- determination of dissolved oxygen using a rapid method with a Fibox 4 fiber-optic analyzer (PreSens, Germany);
- determination of mechanical impurities by filtration followed by weighing the residue;
- determination of the six-component water composition, as well as iron content, using standard titrimetric methods.

## Experimental Section

### Abundance and Activity of Planktonic Sulfidogenic Bacteria at the Field Facilities

For the microbiological studies, samples of produced water from the field's group installations (hereinafter – GIs) were collected.

For the cultivation of SRB, Postgate's medium with the following composition was used:

$\text{KH}_2\text{PO}_4$  – 0.5 g/L,  $\text{NH}_4\text{Cl}$  – 1 g/L,  $\text{Na}_2\text{SO}_4$  – 4 g/L,  $\text{CaCl}_2$  – 0.06 g/L,  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  – 0.06 g/L,  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  – 1 g/L,  $\text{C}_3\text{H}_5\text{O}_3\text{Na}$  (60% solution) – 6 g/L,  $\text{C}_6\text{H}_5\text{O}_7\text{Na}_3 \cdot 5.5\text{H}_2\text{O}$  – 0.3 g/L, yeast extract – 0.1 g/L, microelement solution according to Kevbrin and Zavarzin [4] – 1 mL/L, and 0.04% resazurin solution (1 mL/L).

For the cultivation of TSB and S<sup>o</sup>RB, Widdel's medium [5] with the following composition was used:  $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$  – 4.0 g/L,  $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$  – 0.1 g/L,  $\text{NH}_4\text{Cl}$  – 0.25 g/L,  $\text{KH}_2\text{PO}_4$  – 0.2 g/L,  $\text{KCl}$  – 0.5 g/L,  $\text{NaHCO}_3$  – 0.2 g/L, glucose – 5.0 g/L, peptone – 2.0 g/L, yeast extract – 1.0 g/L, microelement solution according to Kevbrin and Zavarzin [4] – 1 mL/L, and 0.04% resazurin solution (1 mL/L). As an electron acceptor, 2 g/L of thiosulfate ( $\text{Na}_2\text{S}_2\text{O}_3$ ) was added to the medium for TSB, and elemental sulfur (S<sup>o</sup>) for S<sup>o</sup>RB.

NaCl was added to the media according to the experimental conditions, in amounts ranging from 22 to 32 g/L, in accordance with the total salinity of the waters from the studied sites. The media were boiled to remove oxygen, after which ascorbic acid (0.3 g/L) was added as a reducing agent. The pH of the media was adjusted to 7.0–7.2 using 5% HCl or 5%  $\text{NaHCO}_3$  solutions. The media were prepared anaerobically under a nitrogen atmosphere.

Inoculations were carried out using the serial dilution method while maintaining anaerobic conditions. Cultivation was performed at the temperatures recorded during sample collection at the field facilities, ranging from 25 °C to 36 °C, for 15 days. Bacterial growth was monitored by the appearance of a black precipitate in the culture medium. Tab. 1 presents the results of the studies for all three types of sulfidogens: SRB, TSB, and S<sup>o</sup>RB.

A high abundance of SRB was detected at two GIs at sites B and G:  $10^6$  cells/mL at GI-5 and  $10^5$  cells/mL at GI-7. At the remaining GIs, SRB levels ranged from  $10^3$  to  $10^4$  cells/mL.

A high degree of contamination by TSB was observed at three sites (platforms A, C, and B): GI-1 –  $10^6$  cells/mL, GI-7 –  $10^7$  cells/mL, and GI-8 –  $10^6$  cells/mL. At the other sites, their abundance ranged from  $10^3$  to  $10^4$  cells/mL.

The abundance of S<sup>o</sup>RB was significant at five sites, with the highest values observed at GI-1 (A) and GI-2 (B) –  $10^6$  cells/mL, and at GI-7 (G) –  $10^7$  cells/mL.

The study of the microbiological contamination of the field showed that the investigated sites exhibited high abundances not only of SRB but also of other sulfidogenic microorganisms, including thio-sulfate- and sulfur-reducing bacteria.

**Table 1. Content of planktonic sulfidogenic bacteria, cells/ml**

Sampling location	Object	Bacterial content		
		SPB	TSB	S <sup>o</sup> RB
HU-1	A	$10^3$	$10^6$	$10^6$
HU-2	Б	$10^4$	$10^4$	$10^6$
HU-3	B	$10^4$	$10^4$	$10^5$
HU-4	B	$10^4$	$10^3$	$10^3$
HU-5	B	$10^6$	$10^4$	$10^4$
HU-6	B	$10^4$	$10^3$	$10^3$
HU-7	Г	$10^5$	$10^7$	$10^7$
HU-8	Б	$10^4$	$10^6$	$10^5$

The metabolic activity of the studied bacterial groups – SRB, TSB, and S<sup>o</sup>RB – was assessed based on the amount of hydrogen sulfide produced. After 15 days of cultivation, the hydrogen sulfide content in the culture media of the first dilutions was determined by the titrimetric method.

According to the procedure, sulfide ions were precipitated as cadmium sulfide, then oxidized with iodine, and the excess was titrated with a sodium thiosulfate solution.

The concentration of hydrogen sulfide was calculated using formula (1):

$$X = (V_1 - V_2) \cdot 0,852 \cdot 1000/V \quad (1)$$

where  $V_1$  is the volume of the iodine solution added to the test solution,  $\text{cm}^3$ ;  $V_2$  is the volume of sodium thiosulfate solution used for titration,  $\text{cm}^3$ ; 0.852 is the mass of hydrogen sulfide equivalent to the mass of sodium thiosulfate in 1  $\text{cm}^3$  of a solution with an equivalent molar concentration of 0.05 mol/dm<sup>3</sup>, mg; and  $V$  is the volume of the test solution taken for analysis,  $\text{cm}^3$ .

The results of hydrogen sulfide produced by the sulfidogens are presented in Tab. 2.

**Table 2. Hydrogen sulfide content formed by bacteria, mg/L**

Sampling location	Object	Hydrogen sulfide content, produced by bacteria			Total hydrogen sulfide production
		SPB	TSB	S <sup>o</sup> RB	
GI-1	A	762,5	434,5	127,8	1324,8
GI-2	Б	553,8	85,2	59,6	698,6
GI-3	B	660,3	426,0	76,7	1163,0
GI-4	B	153,4	328,0	106,5	587,9
GI-5	B	125,6	196,0	85,2	406,8
GI-6	B	656,0	281,2	98,0	1035,2
GI-7	Г	673,1	579,4	242,8	1495,3
GI-8	Б	170,4	391,9	298,2	860,5

According to the results obtained, SRB produced the highest amount of hydrogen sulfide, while S<sup>o</sup>RB produced the lowest. This outcome reflects the metabolic characteristics of these microbial groups:

SRB largely depend on the presence of oxidized sulfur compounds in the medium, as they carry out sulfate respiration necessary to sustain their viability, whereas S<sup>o</sup>RB, due to their metabolic flexibility,

can utilize sulfur compounds facultatively. Overall, sulfidogens can contribute significantly to the formation of biogenic hydrogen sulfide. Site G of the N field was found to be the most heavily contaminated with sulfidogenic microorganisms exhibiting high hydrogen sulfide productivity.

The results obtained allow us to conclude that there is a biogenic component in the formation of hydrogen sulfide at the field. To determine the contribution of sulfidogenic bacteria to carbon dioxide production, additional research methods are required.

**Abundance and Corrosive Activity of Planktonic and Adherent Sulfidogenic Bacteria in the BCPS (Block Cluster Pumping Station) and VST (Vertical Steel Tank) of the Field**

At four modular horizontal pumping systems (hereinafter – BCPS) – BCPS-1, BCPS-2, BCPS-3, BCPS-4 – and at VST-3 (vertical steel tank) of N field, steel coupons of grade “Steel 20” were installed, with two coupons at each facility. Produced water samples were collected at the same facilities to determine the abundance of planktonic sulfidogenic bacteria and to study the corrosive agents in the waters of the investigated sites.

On the 4th day after the coupons were installed, water circulation in VST-3 was stopped due to technical reasons. Consequently, the coupons remained in VST-3 under stagnant water conditions until their removal. The exposure period of the coupons at the field facilities was 13 days.

The abundance of planktonic sulfidogenic bacteria was determined according to the methodology described above. Bacterial cultivation was carried out under conditions approximating those of the investigated field facilities (temperature and salinity). After the exposure period (13 days), the coupons were removed from the corrosion monitoring units of the facilities and carefully transported to the laboratory in a sterile buffer solution. The same nutrient media used for planktonic bacteria were employed for the study of adherent sulfidogenic bacteria.

The abundance of bacteria adherent to the coupons was determined by inoculating a scrape from a 1 cm<sup>2</sup> area of the coupon surface using the serial tenfold dilution method. For parallel repeat experiments, biofilm was collected from several areas of the coupon. The inoculations were cultivated for 15 days.

The results of the study of planktonic and adherent sulfidogenic bacteria are presented in Tab 3.

**Table 3. The content of planktonic and adherent sulfidogenic bacteria at the field facilities**

Sampling location	Planktonic bacteria, cells/ml			Adhered bacteria, cells/cm <sup>2</sup>		
	SPB	SPB, TSB, S <sup>o</sup> RB	S <sup>o</sup> RB	SPB	SPB, TSB, S <sup>o</sup> RB	S <sup>o</sup> RB
BCPS-1	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>7</sup>	10 <sup>7</sup>	10 <sup>7</sup>	10 <sup>7</sup>
BCPS-2	10 <sup>3</sup>	10 <sup>7</sup>	10 <sup>7</sup>	10 <sup>5</sup>	10 <sup>8</sup>	10 <sup>8</sup>
BCPS-3	10 <sup>6</sup>	10 <sup>6</sup>	10 <sup>6</sup>	10 <sup>6</sup>	10 <sup>7</sup>	10 <sup>7</sup>
BCPS-4	10 <sup>4</sup>	10 <sup>6</sup>	10 <sup>6</sup>	10 <sup>6</sup>	10 <sup>6</sup>	10 <sup>6</sup>
VST-3 (background)	10 <sup>6</sup>	10 <sup>6</sup>	10 <sup>6</sup>	10 <sup>6</sup>	10 <sup>6</sup>	10 <sup>6</sup>

BCPS – Block Cluster Pumping Station; VST – Vertical Steel Tank

The highest abundance of planktonic sulfidogenic bacteria (SRB, TSB, and S<sup>o</sup>RB) was observed at BCPS-2, BCPS-3, and VST-3. The highest abundance of adherent sulfidogenic bacteria was observed at BCPS-2, BCPS-4, and VST-3.

The corrosion rate, as one of the indicators of sulfidogenic bacterial activity, was investigated on coupons installed at BCPS-1, BCPS-2, BCPS-4, and VST-3 (background). Coupons, cleaned of corrosion deposits, washed, and thoroughly dried, were analyzed using the gravimetric method to determine the corrosion rate based on mass loss. The calculation was performed according to formula (2):

$$X = (m_1 - m_2) \cdot 1000 \cdot 24 \cdot 365 / S \cdot T \cdot \rho \cdot 1000 \quad (2)$$

where  $m_1$  is the weight of the control sample (coupon) before testing, g;  $m_2$  is the weight of the control sample (coupon) after testing, g; S is the surface area of the control sample (coupon), m<sup>2</sup> (the surface area of a flat sample is 22.05 × 10<sup>-4</sup> m<sup>2</sup>); T is the duration of the test, h; 24·365 is the conversion factor from hours to years; ρ is the density of the coupon (7820 kg/m<sup>3</sup>); and 1000 is the conversion factor for converting meters to millimeters and grams to kilograms.

The results of the corrosion studies are presented in Tab. 4.

**Table 4. Corrosion rate of coupons, mm/year**

Sampling location	Corrosion rate	Result (average)
BCPS-1	0,66	0,66
	5,664	
BCPS-1	0,53	0,49
	0,44	
BCPS-4	0,33	0,31
	0,29	
VST-3 (background)	9,63	9,78
	9,92	

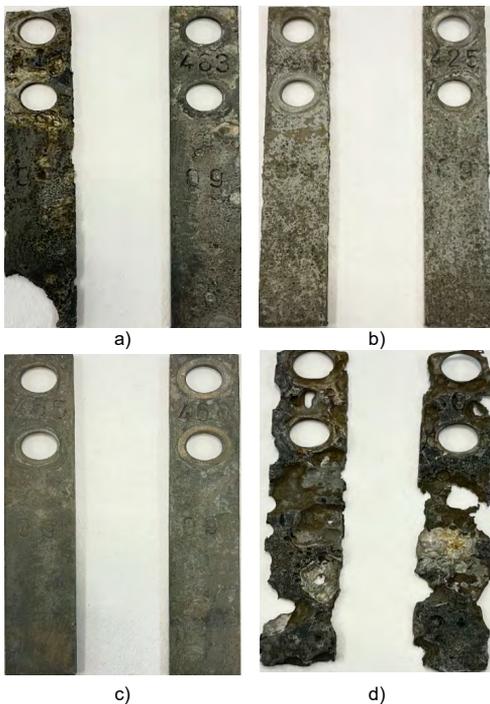
Upon retrieval of the coupons from the facilities, it was found that part of one coupon from BCPS-1 was missing (Fig. 1); therefore, the corrosion rate at this facility was calculated based on the remaining intact coupon.

Fig. 1 shows photographs of the coupons removed from the investigated field facilities.

Visual inspection of the coupons installed at BCPS-1 and BCPS-2 revealed pitting damage, which may result from adherent sulfidogenic bacteria and their metabolic products.

The coupons installed in VST-3 (background), which is not treated with a corrosion inhibitor, exhibited severe corrosion damage. Pitting depressions and pronounced maze corrosion were observed on the coupons.

Corrosive Agents in the BCPS and VST of the Field Within the framework of this study, the water parameters contributing to corrosion were analyzed, namely the contents of hydrogen sulfide, carbon dioxide, oxygen, and mechanical impurities.



**Figure 1. Appearance of the coupons removed from the field facilities**

a) BCPS-1; b) BCPS-2; c) BCPS-4; d) VST-3 (background)  
 Exposure time at field facilities: 13 days.

The hydrogen sulfide content was analyzed according to the methodology described above. The CO<sub>2</sub> content in the water was determined using a method based on the chemical reaction of CO<sub>2</sub> with sodium hydroxide to form sodium carbonate, followed by titration to a pH of 8.4.

The mass fraction of free CO<sub>2</sub> was calculated using formula (3):

$$X = V_1 \cdot 4,4 \cdot 1000/V \tag{3}$$

where V<sub>1</sub> is the volume of sodium hydroxide solution used for titration, cm<sup>3</sup>; 4.4 is the mass of CO<sub>2</sub> equivalent to the mass of sodium hydroxide in 1 cm<sup>3</sup> of a solution with an equivalent molar concentration of 0.01 mol/dm<sup>3</sup>, mg; and V is the capacity of the vessel, cm<sup>3</sup>.

The determination of mechanical impurities was carried out according to a method based on the separation of water-insoluble substances by filtration of the test solution. The residue was then washed with distilled water and weighed.

The mass concentration of insoluble substances was determined using formula (4):

$$X = (m_1 - m_2) \cdot 1000/V \tag{4}$$

where m<sub>1</sub> is the mass of the filter crucible with the insoluble substance, mg; m<sub>2</sub> is the mass of the empty

filter crucible, mg; and V is the volume of the test solution taken for analysis, cm<sup>3</sup>.

The dissolved oxygen content was determined immediately during sample collection, without exposure to atmospheric air, using a Fibox 4 PreSens fiber-optic oxygen analyzer (Germany). The results of the study of corrosive agents are presented in Tab. 5.

**Table 5. Content of corrosion-aggressive agents, mg/l**

Sampling location	Content in water			
	CO <sub>2</sub>	H <sub>2</sub> S	O <sub>2</sub>	mechanical impurities
BCPS-1	78,0	not more than 0.8	0,05	14,4
BCPS-2	87,0	not more than 0.8	0,05	15,6
BCPS-3	80,0	not more than 0.8	0,05	5,5
BCPS-4	82,5	not more than 0.8	0,05	44,3
VST-3 (background)	102,5	2,8	–	37,3

All investigated facilities exhibited significant levels of CO<sub>2</sub>, with the highest concentration observed at the control site, VST-3. Hydrogen sulfide was detected at all sites at concentrations not exceeding 0.8 mg/L, except at VST-3, where it reached 2.8 mg/L. The content of mechanical impurities at VST-3 was also considerable, amounting to 37.3 mg/L.

Mechanical impurities were found in the highest concentration at BCPS-4 (44.3 mg/L) and in the lowest at BCPS-3 (5.5 mg/L).

Since the habitat of the microbial community is the aqueous environment, an analysis of the chemical composition of the waters from the investigated field facilities was conducted (Tab. 6).

The pH of the investigated waters corresponds to a slightly acidic environment, carbonates were not detected, bicarbonates were present in the range of 439.2–658.8 mg/L. Total dissolved solids varied from 27,937.5 to 38,627.9 mg/L. Sulfate ions were not detected in BCPS-1, in the other facilities their content was insignificant – in the range of 23–35.4 mg/L. All samples contained iron in the 2- and 3-valent forms, at 6.3–20.3 mg/L and 0.7–1.4 mg/L, respectively.

The composition of the investigated waters contains the necessary elements for the growth and development of sulfidogenic bacteria. The mineralization of the formation pressure maintenance system provides favorable conditions for bacterial growth and development. The absence or low content of sulfur compounds in the medium did not limit the growth of the studied microorganisms, since, due to their flexible metabolism, sulfidogenic bacteria can utilize oxidized sulfur compounds from the oil, developing at the oil–water phase boundary, including SRB.

**Table 6. Chemical composition of water from field facilities**

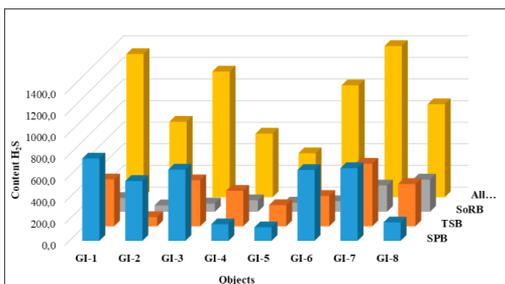
Parameter name	Results				
	BCPS-1	BCPS-2	BCPS-3	BCPS-4	VST-3 (background)
pH	6,4	6,4	6,4	6,4	6,5
Calcium (Ca <sup>2+</sup> ), mg/dm <sup>3</sup>	1102,2	1102,2	1002,0	1302,6	1302,6
Magnesium (Mg <sup>2+</sup> ), mg/dm <sup>3</sup>	425,6	364,8	668,8	851,2	547,2
Potassium and Sodium (Na <sup>+</sup> + K <sup>+</sup> ), mg/dm <sup>3</sup>	8963,3	9198,6	8959,8	12205,7	11685,1
Chlorides (Cl <sup>-</sup> ), mg/dm <sup>3</sup>	17007,1	17175,5	17512,3	23574,3	21890,4
Sulfates (SO <sub>4</sub> <sup>2-</sup> ), mg/dm <sup>3</sup>	not detected	23,0	28,8	35,4	28,8
Carbonates (CO <sub>3</sub> <sup>2-</sup> ), mg/dm <sup>3</sup>	not detected	not detected	not detected	not detected	not detected
Bicarbonates (HCO <sub>3</sub> <sup>-</sup> ), mg/dm <sup>3</sup>	439,2	463,6	451,4	658,8	610,0
Ferrous iron (Fe <sup>2+</sup> ), mg/dm <sup>3</sup>	20,3	18,9	19,6	6,3	-
Ferric iron (Fe <sup>3+</sup> ), mg/dm <sup>3</sup>	0,7	0,7	0,7	1,4	-
Total dissolved solids, mg/dm <sup>3</sup>	27937,5	28327,8	28623,1	38627,9	36064,1
Total water hardness, mg-eq./dm <sup>3</sup>	90,0	85,0	10 <sup>0</sup> ,0	135,0	110,0
Water type according to Sulin	Cl-Ca	Cl-Ca	Cl-Ca	Cl-Ca	Cl-Ca

## Results and Discussion

The study of the abundance of all sulfidogenic bacteria revealed a high level of contamination by fermentative bacteria (TSB, S<sup>o</sup>RB), with the highest level observed for S<sup>o</sup>RB at most facilities. This may be due to the significant sulfur content of the oil at the field and the flexible metabolic capabilities of the bacteria.

It should be noted that a high abundance of sulfidogenic bacteria was observed at site G (GI-7), where waterflooding is being conducted.

Data analysis showed that there is no direct correlation between the method of field development and bacterial abundance. The study of the metabolic activity of sulfidogenic bacteria revealed that SRB contribute the most to hydrogen sulfide formation, while S<sup>o</sup>RB contribute the least. However, fermentative bacteria, due to their high abundance under favorable conditions, can produce a significant amount of hydrogen sulfide, and the combined contribution of all sulfidogens makes a substantial contribution to the sulfide generation process at the field (Fig. 2). Therefore, during microbiological monitoring of produced waters, both SRB and fermentative bacteria should be studied.



**Figure 2. Amount of hydrogen sulfide formed by different physiological groups of bacteria from various field facilities, individually and collectively, mg/l**

To analyze the causes of corrosion processes at the field facilities, the spectrum of investigated corrosive factors was compared with the metal corrosion rate (Tab. 7).

At the investigated field, a corrosion inhibitor is used for protection: at BCPS-1 and BCPS-2, it is applied at a dosage of 7.5–8 g/t, and at BCPS-3 and BCPS-4, at a dosage of 20–25 g/t, which allows controlling the corrosion rate at BCPS-1, BCPS-2, and BCPS-4.

All facilities exhibit high levels of planktonic (10<sup>5</sup>–10<sup>8</sup> cells/mL) and adherent (10<sup>6</sup>–10<sup>8</sup> cells/mL) sulfidogenic bacteria.

The water in VST-3 was characterized by a high abundance of sulfidogenic bacteria and a high corrosion rate, which results from the simultaneous combination of several factors: the formation of a favorable environment for microbial growth in stagnant conditions, prolonged water stagnation (10 days), high concentrations of carbon dioxide and hydrogen sulfide, and, most importantly, the absence of corrosion inhibitor protection. The factors listed above indicate that stagnant conditions promote the intensification of corrosion processes compared to environments with a continuous flow of produced fluids. According to the process flow scheme, produced water from GI-7 (G), GMU-1 (A), and GI-8 (B) is directed to the oil preliminary treatment unit, and then to BCPS-1, 2, and 3. Produced water from GI-3, 4, 5, 6 at site B and GI-2 at the adjacent site B flows into VST-3, and subsequently to BCPS-4.

In the waters of VST-3 and BCPS-4, where the water is primarily from site B, high concentrations of carbon dioxide, hydrogen sulfide, and mechanical impurities were observed. These components may cause hydrogen sulfide corrosion, CO<sub>2</sub> corrosion, and abrasive wear of the lower sections of metal pipes, respectively.

Table 7. Range of corrosion factors and corrosion rate at field facilities

Parameter name	Sampling location				
	BCPS-1	BCPS-2	BCPS-3	BCPS-4	VST-3 (background)
Corrosion rate, mm/g	0,66	0,49	–	0,31	9,78
Number of planktonic sulphidogens, cells/ml	10 <sup>6</sup>	10 <sup>7</sup>	10 <sup>8</sup>	10 <sup>6</sup>	10 <sup>8</sup>
Number of adhered sulfides, cells/cm <sup>2</sup>	10 <sup>7</sup>	10 <sup>8</sup>	10 <sup>7</sup>	10 <sup>8</sup>	10 <sup>6</sup>
pH	6,4	6,4	6,4	6,4	6,5
Total dissolved solids, mg/dm <sup>3</sup>	27937,5	28327,8	28623,1	38627,9	36064,1
Chlorides (Cl <sup>-</sup> ), mg/dm <sup>3</sup>	17007,1	17175,5	17512,3	23574,3	21890,4
Sulfates (SO <sub>4</sub> <sup>2-</sup> ), mg/dm <sup>3</sup>	not detected	23,0	28,8	35,4	28,8
Bicarbonates (HCO <sub>3</sub> <sup>-</sup> ), mg/dm <sup>3</sup>	439,2	463,6	451,4	658,8	610,0
CO <sub>2</sub> in water, mg/dm <sup>3</sup>	78,0	87,0	80,0	82,5	102,5
H <sub>2</sub> S in water, mg/dm <sup>3</sup>	not more than 0.8	2,8			
O <sub>2</sub> in water, mg/dm <sup>3</sup>	0,05	0,05	0,05	0,05	–
Mechanical impurities, mg/dm <sup>3</sup>	14,4	15,6	5,5	44,3	37,3
Temperature, °C	36	38	35	34	34
Ferrous iron (Fe <sup>2+</sup> ), mg/dm <sup>3</sup>	20,3	18,9	19,6	6,3	–
Ferric iron (Fe <sup>3+</sup> ), mg/dm <sup>3</sup>	0,7	0,7	0,7	1,4	–

## Conclusion

The analysis of the results of the study of corrosive factors showed that site B of the field has the highest corrosion potential. It is known that thermal recovery technology is applied at site B. At sites A and B, production is carried out using alternating thermal recovery and waterflooding with produced water. At site G, production is carried out solely by waterflooding with produced water. At all sites, particularly at site B, viable mesophilic bacteria

growing at 30–40°C were detected, indicating that there are zones within the reservoir with relatively favorable temperature conditions for the development of the formation microflora. The abundance of sulfidogenic bacteria at site B is comparable to their abundance at other sites of the field; however, this site is characterized by a significant content of corrosive gases. This suggests that while there is a biogenic component in the gas accumulation at site B, the process is primarily the result of thermochemical reactions.

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## ДОПОЛНИТЕЛЬНО

**Источник финансирования.** Авторы заявляют об отсутствии внешнего финансирования при проведении исследования.

**Конфликт интересов.** Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

**Вклад авторов.** Все авторы подтверждают соответствие своего авторства международным критериям ICMJE (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией). Наибольший вклад распределён следующим образом: Бисенова М.А. – визуализация, сбор и обработка материалов, курирование данных, анализ полученных материалов, написание текста; Биджиева С.Х. – администрирование проекта, концептуализация и дизайн исследования, анализ полученных материалов, написание текста.

## REFERENCES

1. Yelemanov BD, Gershtansky OS. *Oslozheniya pri dobyche nefi*. Moscow: Nauka; 2007. 420 p. (In Russ).
2. Sokolova DS, Semenova EM, Grouzdev DS, et al. Sulfidogenic Microbial Communities of the Uzen High-Temperature Oil Field in Kazakhstan. *Microorganisms*. 2021;9(9):1818. doi: [10.3390/microorganisms9091818](https://doi.org/10.3390/microorganisms9091818).
3. Puentes-Cala E, Tapia-Perdomo V, Espinosa-Valbuena D, et al. Microbiologically influenced corrosion: The gap in the field. *Frontiers in Environmental Science*. 2022;10:924842. doi: [10.3389/fenvs.2022.924842](https://doi.org/10.3389/fenvs.2022.924842).

4. Kevbrin VV, Zavarzin GA. Vliyaniye soyedineniy sery na rost galofil'noy gomoatsetatnoy bakterii Acetohalobium arabaticum. Microbiology. 1992;61(5):812–817.
5. Widdel FF, Bak R. Gram negative mesophilic sulfate reducing bacteria. In: Balows A, Trüper HG, Dworkin M, Harder W, Schleifer K, editors. *The Prokaryotes: a Handbook on the Biology of Bacteria: Ecophysiology, Isolation, Identification, Applications*. Berlin: Springer; 2002. P:3352–3378.

## СПИСОК ИСПОЛЬЗОВАННОЙ ЛИТЕРАТУРЫ

1. Елеманов Б.Д., Герштанский О.С. Осложнения при добыче нефти. Москва : Наука, 2007. 420 с.
2. Sokolova D.S., Semenova E.M., Grouzdev D.S., et al. Sulfidogenic Microbial Communities of the Uzen High-Temperature Oil Field in Kazakhstan // Microorganisms. 2021. Vol. 9, Issue 9. doi: [10.3390/microorganisms9091818](https://doi.org/10.3390/microorganisms9091818).
3. Puentes-Cala E., Tapia-Perdomo V., Espinosa-Valbuena D., et al. Microbiologically influenced corrosion: The gap in the field // Frontiers in Environmental Science. 2022. Vol. 10. doi: [10.3389/fenvs.2022.924842](https://doi.org/10.3389/fenvs.2022.924842).
4. Кевбрин В.В., Заварзин Г.А. Влияние соединений серы на рост галофильной гомоацетатной бактерии Acetohalobium arabaticum // Микробиология. 1992. Т. 61, №5. С. 812–817.
5. Widdel F.F., Bak R. Gram negative mesophilic sulfate reducing bacteria. In: Balows A., Trüper H.G., Dworkin M., Harder W., Schleifer K., editors. *The Prokaryotes: a Handbook on the Biology of Bacteria: Ecophysiology, Isolation, Identification, Applications*. Berlin : Springer, 2002. P. 3352–3378.

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