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Investigation of the behavior of sodium dichloroisocyanurate in aqueous solutions

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Abstract: Global gold consumption has steadily increased in recent decades, driven by expanding industrial applications and reserve accumulation by many countries. In parallel, depletion of high-grade deposits has shifted processing toward low-grade and refractory ores. These trends—together with tighter environmental regulations—highlight the need for alternative lixiviants for gold extraction. Although cyanide remains the industry standard, it is highly toxic and often ineffective for refractory sulfide ores. Other systems—thiosulfate (including ammoniacal thiosulfate), thiourea, and bromide/iodide lixiviants—are used far less frequently due to significant disadvantages. Among acidic chloride lixiviants, sodium dichloroisocyanurate (NaDCC) was investigated as a promising candidate. Use of NaDCC requires strongly acidic solutions (pH < 1.0) and an excess of Cl^-, i.e., conditions consistent with the stability domain of the Au(III) chloride complex ($AuCl_4^-$). Using the rotating-disk technique, we examined the effects of temperature, disk rotation rate, and HCl concentration on the specific dissolution rate of the reagent (NaDCC), as well as on solution pH and redox potential (Eh). NaDCC hydrolyzes in water to form hypochlorous acid (HClO)—the primary source of active chlorine—while the concurrent pH decrease arises from formation of weak acids (hypochlorous and cyanuric). Adding HCl to NaDCC solutions generates molecular chlorine (Cl_2), which evolves once its solubility limit is exceeded. Gold-dissolution tests across NaDCC and HCl concentrations identified an optimum at [HCl] = 14.4 g/dm^3 and [NaDCC] = 3.0 g/dm^3, yielding a maximum gold dissolution rate of $\upsilon_{Au} = 0.118$ mg/(cm^2·min).

Keywords: sodium dichloroisocyanurate (NaDCC), cyanuric acid, hydrochloric acid, rotating-disk, gold leaching, dissolution.

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Изучение поведения дихлоризоцианурата натрия в водных растворах

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Аннотация: В последние десятилетия мировое потребление золота стабильно повышается, что обусловлено его возрастающей ролью как промышленного металла и стремлением накопления многими странами золотых резервов. Одновременно с этим наблюдается истощение золотосодержащих месторождений, что ведет к вовлечению в переработку бедных и упорных руд. Такое

изменение сырьевой базы и усиление экологических требований к металлургическому производству делает очень актуальной задачей поиск новых реагентов для выщелачивания золота. Традиционно используемые для этой цели цианистые растворы имеют высокую токсичность и низкую эффективность при выщелачивании золота из упорных и сульфидных руд. Прочие растворители – тиосульфатные и аммиачно-тиосульфатные растворы, тиомочевина, бромиды и йодиды, используются гораздо реже, так как имеют целый ряд существенных недостатков. Вариантом эффективного альтернативного реагента для выщелачивания золота из различного сырья могут стать хлоридные растворители, например дихлоризоцианурат натрия (ДЦН). Его использование предполагает кислый характер раствора pH < 1,0 и избыток Cl^--ионов. Поэтому для практического применения ДЦН при гидрометаллургической переработке золотосодержащих материалов необходимо изучение поведения данного реагента в условиях, соответствующих области существования хлоридного комплекса золота (III). Эксперименты проводили методом вращающегося диска. Исследовали влияние температуры, скорости вращения диска, концентрации соляной кислоты на удельную скорость растворения ДЦН, величину pH и окислительно-восстановительный потенциал растворов. Установлено, что при растворении ДЦН в воде происходит его гидролиз с образованием хлорноватистой кислоты (HClO), которая служит основным источником активного хлора. Сопровождающееся при этом снижение pH связано с образованием слабых кислот – хлорноватистой и циануровой. Введение соляной кислоты в водный раствор ДЦН приводит к образованию молекулярного хлора, который при достижении своей предельной растворимости переходит в газообразное состояние. Проведены экспериментальные исследования по определению скорости растворения золота при различных концентрациях ДЦН и соляной кислоты. Установлено, что при C_{HCl} = 14,4 г/дм^3 и $C_{ДЦН}$ = 3,0 г/дм^3 достигается максимальная скорость растворения υ_{Au} = 0,118 мг/(см^2·мин).

Ключевые слова: дихлоризоцианурат натрия (ДЦН), циануровая кислота, соляная кислота, вращающийся диск, растворение, золото.

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Introduction

Global gold consumption has risen from about 3500 to nearly 5000 t/year over the past two decades [1], driven by its expanding use in electronics and its role as an investment asset under conditions of economic instability. Approximately 90 % of gold is produced by the cyanidation process, which remains an effective and economical method for extracting the metal from both primary and secondary resources [2]. However, cyanide is associated with severe drawbacks: high biological toxicity, excessively long leaching times, and poor efficiency in the treatment of refractory and sulfide ores. Gold-mining operations have also been implicated in major environmental accidents caused by cyanide spills into surface waters — for example, in Russia (2014, 2019), Canada (2024), Mexico (2018), Papua New Guinea (2000), and Kyrgyzstan (1998, 2021). These risks underscore the urgent need to identify alternative lixiviants for gold in order to minimize the environmental impact of Au-bearing material processing [3].

It is well established that gold leaching requires the simultaneous presence of a complexing agent and an oxidant. Among cyanide-free complexing systems for gold, the most studied are based on inorganic reagents: thiosulfate, ammoniacal thiosulfate, thiourea, chloride, iodide, and bromide solutions [4—6]. In addition, a wide range of organic compounds have been proposed as potential gold lixiviants, including humic substances and amino acids (glycine, alanine, valine, aspartic acid, phenylalanine, asparagine, cysteine, etc.), malononitrile, β-hydroxynitriles, potassium tricyanomethanid, calcium cyanamide, dibromodimethylhydantoin, and dimethyl sulfoxide [7—10].

The use of halogen-based solutions, particularly those containing chlorine, dates back to the Middle Ages [11]. Halogen leaching systems combine the dual functions of oxidant and complexing agent [12]. Table 1 summarizes reported gold dissolution rates in halide media together with the corresponding operating conditions. Chloride systems — including chlorine, hypochlorous acid, hypochlorites, and iron or copper chlorides — have demonstrated high effectiveness for dissolving gold. Thermodynamically, chlorine and hypochlorous acid have relatively high standard potentials (E^0 = 1.36÷1.49 V), compared with iodides (E^0 = 0.54 V) and bromides (E^0 = 1.1 V). The $[AuCl_4]^-$ complex is stable in the presence of excess chloride ions.

Table 1. **Properties of halide-based gold lixiviants**

Таблица 1. Свойства растворителей золота на основе галогенидов

Process type	Gold dissolution rate, mg/(m^2·s)	Conditions	Advantages	Disadvantages	Ref.
Hydrochlorination with OCl^-	36.1	[NaCl] = 100 g/dm^3 [OCl^-] = 10 g/dm^3 pH = 6	• High dissolution rate • Applicable to a variety of feed materials • Wide choice of oxidants	• High corrosivity • Requires maintaining low pH	[13]
Chloride leaching with $FeCl_3$	143.8	[$FeCl_3$] = 27.9 g/dm^3 [NaCl] = 141.8 g/dm^3 pH ≈ 1.0 t = 95 °C	• High dissolution rate • Reagents are readily available	• Requires elevated temperature • Possible $Fe(OH)_3$ formation • Narrow pH range	[14]
Bromide leaching	19.7	[Br^-] = 2 g/dm^3 pH = 4 t = 25 °C	• High dissolution rate • Applicable to a variety of feed materials	• High corrosivity • High lixiviant consumption • Complicated gold recovery from solution • Surface passivation • Process control difficulties	[15]
Iodide leaching	6.6	[NaI] = 1.5 g/dm^3 [I_2] = 1.27 g/dm^3 pH = 4÷6 t = 23 °C	• Effective for refractory and sulfide ores • Lixiviants can be regenerated • Low corrosivity	• High lixiviant consumption • Instability of iodides • Process control difficulties • Solution instability • Impurity sensitivity • Low gold dissolution rate	[16]

Chlorine-containing reagents, unlike bromine and iodine, are inexpensive, widely produced, and less hazardous when handled under standard safety protocols. By contrast, bromide- and iodide-based systems are more demanding in terms of storage and handling and are considerably more costly, which limits their large-scale industrial application.

The chlorination process is highly versatile and enables the recovery of gold from mineral feed of almost any composition [17]. An important advantage of this technology is its suitability for comprehensive processing, allowing not only gold but also other valuable metals, such as the platinum-group metals, to be recovered [18—20].

A key requirement for effective chloride leaching of gold is the presence of an oxidant with high redox potential that remains stable under leaching conditions (pH, temperature, solution composition). The oxidants most commonly employed in hydrochlorination and chloride leaching include chlorine gas, hypochlorous acid (HClO), hypochlorites, ferric iron, and cupric copper [21—23]. To enhance the efficiency of gold

leaching, particular attention has been given to oxidants capable of generating active chlorine directly in solution. Among such reagents are chlorine-containing organic compounds, such as trichloroisocyanuric acid (TCCA, $C_3N_3O_3Cl_3$) and sodium dichloroisocyanurate (NaDCC, $C_3Cl_2N_3O_3Na$). These substances are derivatives of cyanuric acid and act as oxidants and sources of active chlorine widely used in sanitation and water treatment.

Studies [24—27] on the application of TCCA to Au-bearing materials confirm its high effectiveness. NaDCC can likewise serve as a controlled and environmentally safer oxidative medium for gold dissolution in chloride systems. However, NaDCC has been much less studied as a gold lixiviant, even though its dissolution rate is somewhat higher and its working pH range is broader than those of TCCA [28]. Moreover, unlike TCCA, NaDCC is less susceptible to degradation by moisture and elevated temperatures during long-term storage, which is a critical factor for gold-mining operations in remote regions [29].

Our earlier work [30; 31] on hydrochlorination of oxidized Au-bearing ore with NaDCC addition demonstrated higher dissolution rates and more complete gold recovery compared with conventional cyanidation. We also identified process parameters that allow recovery of over 90 % of gold from a gravity concentrate [32]. At present, however, no data are available on how process conditions affect the dissolution rate of NaDCC, its speciation in solution, or changes in solution redox potential (Eh).

The present study addresses the influence of temperature, initial hydrochloric acid concentration, and disk rotation speed on the dissolution rate of NaDCC, as well as the effects of hydrochloric acid and oxidant (NaDCC) concentrations on the rate of gold dissolution.

Experimental procedure

The experiments employed tablets ("Altaykhimia" LLC, Russia) containing 84 % sodium dichloroisocyanurate (NaDCC) and reagent-grade hydrochloric acid. Dissolution tests were carried out using the rotating-disk technique with the setup shown in Fig. 1. A 26-mm-diameter tablet was fixed in a holder made of inert material and mounted on a top-driven stirrer. The reactor was charged with 50 mL of aqueous solution, sealed, and heated to the desired temperature using a heating mantle. The tablet holder was then immersed in the reactor and stirring was initiated. During the experiments,

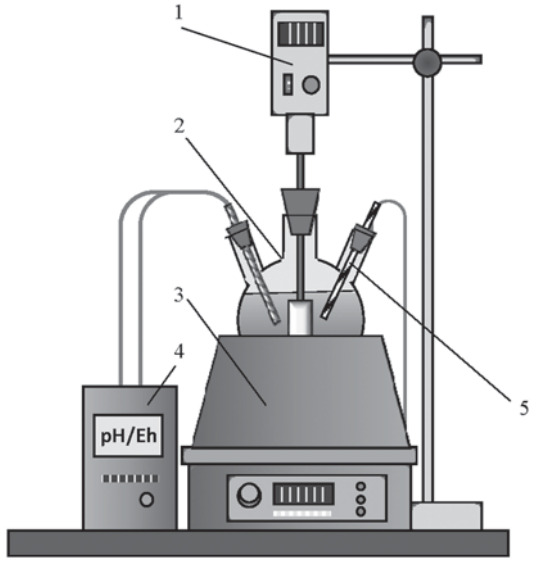

Fig. 1. Experimental setup for studying NaDCC dissolution

1 – top-driven stirrer with disc; ***2*** – three-neck flask with solution; ***3*** – heating mantle; ***4*** – pH meter; ***5*** – temperature probe

Рис. 1. Установка для изучения растворения ДЦН

1 – верхнеприводная мешалка с диском; ***2*** – трехгорлая колба с раствором; ***3*** – колбонагреватель; ***4*** – pH-метр; ***5*** – термодатчик

the temperature was automatically maintained within ±2 °C, and the solution pH and redox potential (Eh) were monitored with a pH-410 meter (Aquilon JSC, Russia). Tablet mass loss was determined by weighing before and after each test.

The effects of temperature (25—70 °C), disk rotation speed (50—900 rpm), and initial HCl concentration ([HCl] = 0.1÷30 g/dm^3) on the specific dissolution rate of NaDCC (υ_{NaDCC}), solution pH, and redox potential (Eh) were investigated. The effect of NaDCC concentration ([NaDCC] = 0.5÷10 g/dm^3) on pH and Eh of aqueous solutions was also determined. The dissolved mass of NaDCC (m_{NaDCC}) was calculated based on its content in the tablet. The specific dissolution rate was determined from equation

$$\upsilon_{NaDCC} = \frac{m_{\tau\,NaDCC}}{\tau S}, \qquad (1)$$

where $m_{\tau NaDCC}$ is the mass of NaDCC dissolved during time τ, mg; τ is the test duration, min; S = 5.31 cm^2 is the disk surface area.

Gold dissolution in NaDCC solutions was studied using the rotating-disk technique. A 10-mm-diameter disk of metallic gold (99.9 %) was mounted in a holder made of inert material. Prior to each experi-

ment, the disk surface was polished with GOI polishing paste (chromium oxide—based), rinsed with ethanol and distilled water, and dried in air. Leaching tests were carried out in 50 mL of solution at 25 °C and 300 rpm. The effects of [NaDCC] (1—5 g/dm^3) and [HCl] (0—21.6 g/dm^3) on the gold dissolution rate were evaluated. After each experiment, the solution was filtered and analyzed by atomic absorption spectrometry (novAA 300, Analytik Jena, Germany) at a wavelength of 242.8 nm. The specific gold dissolution rate was calculated from equation

$$\upsilon_{Au} = \frac{C_{Au}V}{S\tau}, \quad (2)$$

where C_{Au} is the gold concentration in solution, mg/dm^3; V is the solution volume, dm^3; S is the disk surface area, cm^2; τ is the test duration, min.

All experiments were conducted in triplicate under identical conditions, with deviations between parallel measurements not exceeding 5 %.

Results and discussion

Sodium dichloroisocyanurate (NaDCC) undergoes dissociation and hydrolysis upon contact with water, yielding cyanuric acid ($C_3H_3N_3O_3$), hypochlorous acid (HClO), and sodium hydroxide (NaOH). The overall reaction can be represented as:

$$NaC_3Cl_2N_3O_3 + 3H_2O = $$
$$= C_3H_3N_3O_3 + 2\,HClO + NaOH. \quad (3)$$

According to reaction (3), sodium hydroxide is formed as a product. In practice, however, the observed decrease in solution pH (Fig. 2, *a*) is due to the accumulation of weak acids — hypochlorous and cyanuric — which partially dissociate and increase the hydrogen ion concentration. Furthermore, hypochlorous acid may undergo disproportionation with H^+ release, further acidifying the medium.

Owing to the high standard redox potential of hypochlorous acid, NaDCC dissolution resulted in an increase in solution Eh to 1000—1180 mV and a decrease in pH to 3.7—2.7 at [NaDCC] = 1÷10 g/dm^3 (Fig. 2). Cyanuric acid did not directly affect Eh but stabilized Cl-containing species and acted as a buffer.

The high redox potential of aqueous NaDCC solutions suggests that it can be applied for gold dissolution in chloride media. It is well established that gold oxidation in hydrochloric acid solutions begins at solution Eh values above 1000—1200 mV

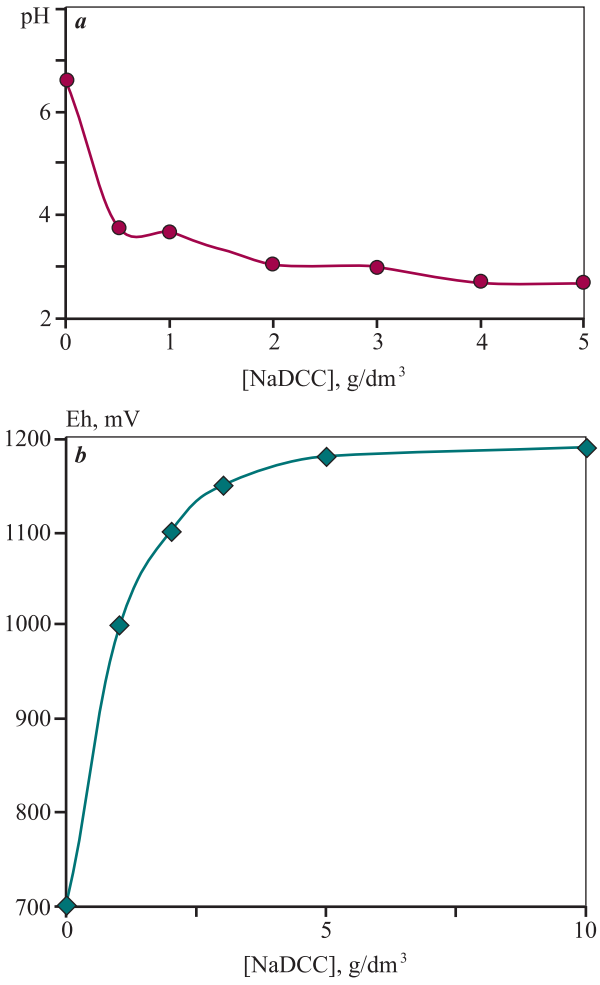

Fig. 2. Effect of sodium dichloroisocyanurate concentration on pH (***a***) and redox potential (Eh) (***b***) of aqueous solution

Рис. 2. Влияние концентрации дихлоризоцианурата натрия на pH (***a***) и ОВП (***b***) водного раствора

(Fig. 3). In chlorine-chloride systems, NaDCC serves as a source of active chlorine, thereby acting as the oxidant.

NaDCC dissolution with the release of active chlorine in water and weakly acidic solutions occurs slowly, что хорошо синхронизируется с растворением золота. The gold chloride complex $[AuCl_4]^-$ is less stable than the cyanide complex $[Au(CN)_2]^-$, with stability constants (lgβ) of 26 and 38.3, respectively [1]. To ensure the stability of the gold chloride complex, pH values below 1.0 and an excess of chloride ions are required [1]. Therefore, for practical application of NaDCC in hydrometallurgical processing of Au-bearing materials, it is necessary to study the behavior of this oxidant under conditions corresponding to the stability region of the Au(III) chloride complex.

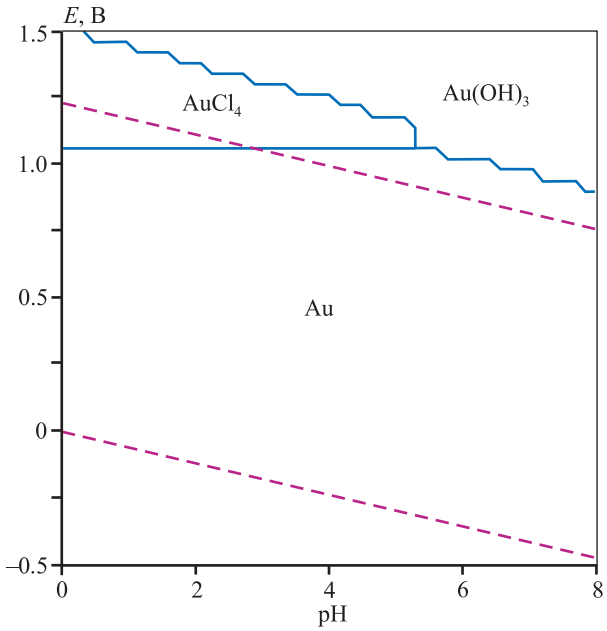

Fig. 3. Pourbaix diagram for the Au–Cl–H_2O system
[Cl] = 0.5 M, [Au] = $1 \cdot 10^{-5}$ M, ionic strength – 0.5 M,
t = 25 °C
Diagram generated using the Medusa–Hydra software

Рис. 3. Диаграмма Пурбе для системы Au–Cl–H_2O
[Cl] = 0,5 М, [Au] = $1 \cdot 10^{-5}$ М, ионная сила раствора – 0,5 М,
t = 25 °C
Диаграмма построена с применением программы
Medusa-Hydra

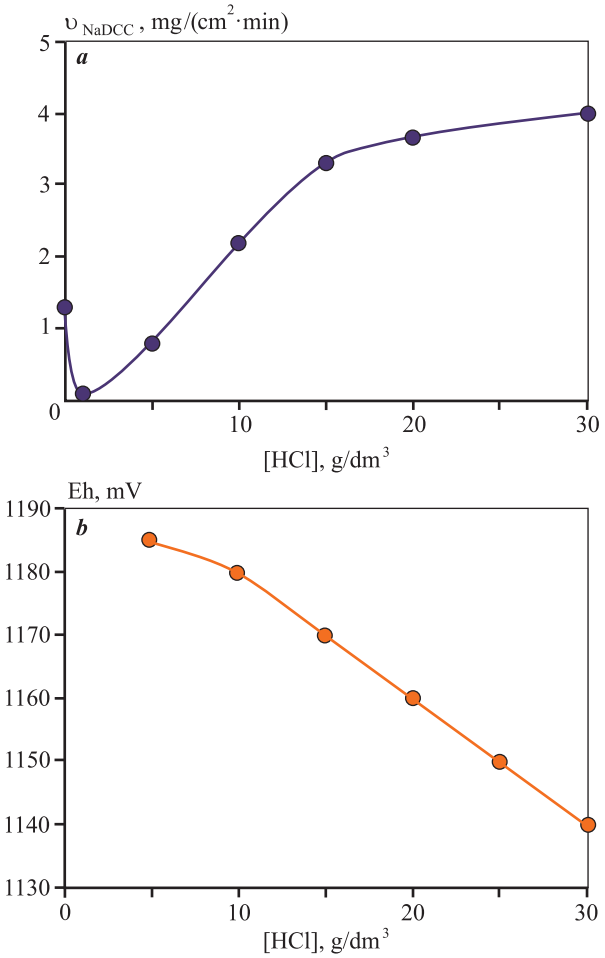

Fig. 4. Effect of hydrochloric acid concentration on the dissolution rate of NaDCC (***a***) and solution redox potential (Eh) (***b***) at [NaDCC] = 3 g/dm^3, t = 25 °C

Рис. 4. Влияние концентрации соляной кислоты на скорость растворения ДЦН (***a***) и величину ОВП водных растворов (***b***) при $C_{ДЦН}$ = 3 г/дм^3, t = 25 °C

Under such conditions, reactions involving NaDCC and hypochlorous acid occur with the release of chlorine gas:

$$NaC_3Cl_2N_3O_3 + 3HCl = C_3H_3N_3O_3 + 2Cl_2\uparrow + NaCl, \quad (4)$$

$$HClO + HCl = Cl_2\uparrow + H_2O. \quad (5)$$

Molecular chlorine is readily soluble in aqueous solutions (0.63 g/100 g water at 25 °C [33]). Once the solubility limit is reached, chlorine escapes to the atmosphere.

As seen from the data (Fig. 4, *a*), the dissolution rate of NaDCC initially decreased with the addition of small amounts of HCl, but began to rise again once [HCl] reached 1 g/dm^3. Notably, at [HCl] = = 1÷5 g/dm^3 the dissolution rate was lower than in pure water, amounting to 0.1—0.8 mg/(cm^2·min), while a further increase in [HCl] up to 30 g/dm^3 enhanced the rate to 4 mg/(cm^2·min). The most probable explanation for this behavior is diffusion limitation. It has been reported [34] that trichloroisocyanuric acid has low solubility (0.7 %), and during NaDCC dissolution it can precipitate on the tablet surface, forming a diffusion barrier. The subsequent increase in υ_{NaDCC} at higher [HCl] (>5—10 g/dm^3) is associated with the decomposition of trichloroisocyanuric acid, accompanied by intensive release of gaseous chlorine and formation of cyanuric acid.

The key parameter of this system in relation to gold dissolution is the solution redox potential. Adding HCl to an aqueous NaDCC solution ([NaDCC] = = 3 g/dm^3) increased Eh from 1150 mV at [HCl] = = 0 to 1185 mV at [HCl] = 5 g/dm^3 (Fig. 4, *b*). Across the full [HCl] range studied, further acid addition led to a gradual decrease in Eh to 1140 mV at [HCl] = = 30 g/dm^3. Although thermodynamically, an increase

in proton concentration should raise the Eh of the HClO/Cl^- couple, the excess hydrochloric acid promotes decomposition of NaDCC and hypochlorous acid according to reactions (4) and (5), producing molecular chlorine. Since Cl_2 has a lower redox potential ($E^0_{Cl_2/Cl^-}$ = +1.36 V) than hypochlorous acid (E^0_{HClO/Cl^-} = +1.49 V) the overall result is a reduction in the concentration of active oxidants and a corresponding decrease in solution Eh.

At [HCl] = 15 g/dm^3, the dissolution rate of NaDCC increased exponentially with temperature from 2.81 to 13.61 mg/(cm^2·min) over the range 25—70 °C (Fig. 5 , *a*). The $\upsilon_{NaDCC} = f(t)$ curve can be divided into two regions: the first between 25—45 °C, and the second between 45—70 °C. In the lower range, the dissolution rate increased by 0.133 mg/(cm^2·min) per °C, while in the higher range the increment was 0.326 mg/(cm^2·min) per °C. The acceleration of NaDCC dissolution at elevated temperatures can be attributed to several factors:

— enhanced decomposition of hypochlorous acid with Cl_2 formation and reduced solubility of Cl_2, shifting reactions (4) and (5) to the right;

— increased solubility of cyanuric acid, which at moderate temperatures tends to passivate the reactive surface [7].

When the disk rotation speed was increased from 50 to 900 rpm, the dissolution rate of NaDCC rose from 0.8 to 5.3 mg/(cm^2·min) at [HCl] = 15 g/dm^3 (Fig. 5, *b*), consistent with enhanced mass transfer at the solid—liquid interface. Thus, NaDCC solutions in the presence of hydrochloric acid exhibit high Eh values, confirming their potential as alternative oxidants for gold leaching.

The next stage examined the effect of [HCl] and [NaDCC] on the gold dissolution rate (υ_{Au}). The results are given in Table 2. In pure aqueous NaDCC solutions, only a small amount of gold entered solution at [NaDCC] = 3÷5 g/dm^3, with υ_{Au} = 0.001÷÷0.051 mg/(cm^2·min). Increasing [HCl] from 1.44 to 14.4 g/dm^3 at constant [NaDCC] enhanced gold dissolution. For instance, at [HCl] = 1.44 g/dm^3, υ_{Au} increased from 0.018 to 0.052 mg/(cm^2·min) as [NaDCC] rose from 1 to 5 g/dm^3, respectively. At higher acid concentration ([HCl] = 21.6 g/dm^3), the gold dissolution rate declined to 0.05—0.08 mg/(cm^2·min). The

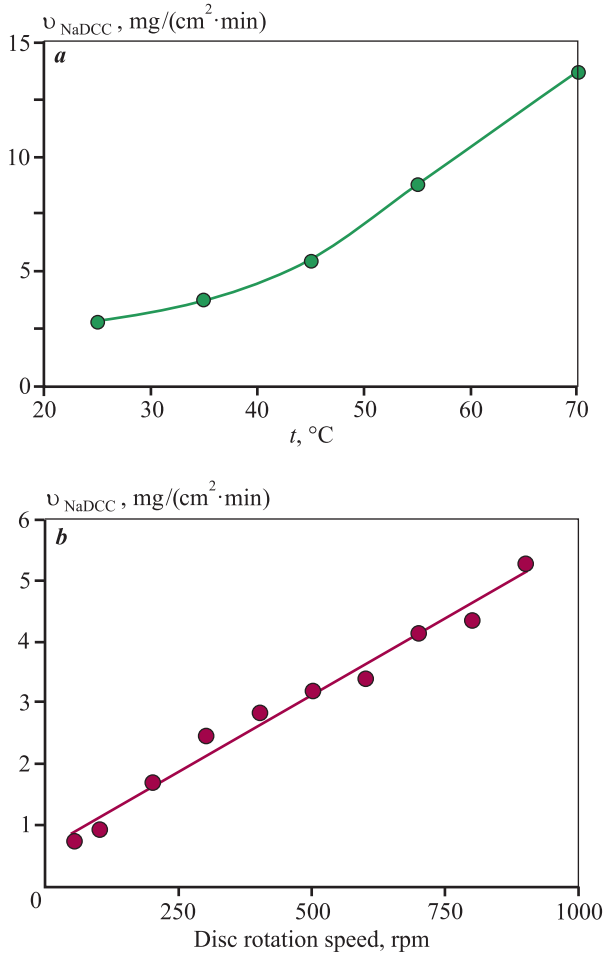

Fig. 5. Effect of temperature (***a***) and disc rotation speed (***b***) on the dissolution rate of NaDCC in hydrochloric acid solutions ([HCl] = 15 g/dm^3)

Рис. 5. Влияние температуры (***a***) и скорости вращения диска (***b***) на скорость растворения ДЦН в растворах соляной кислоты (C_{HCl} = 15 г/дм^3)

Table 2. **Effect of HCl and NaDCC concentrations on the gold dissolution rate (*n* = 300 rpm, *t* = 25 °C, *r* = 5 mm)**

Таблица 2. Влияние концентраций HCl и ДЦН на скорость растворения золотого диска (*n* = 300 об/мин, *t* = 25 °C, *r* = 5 мм)

[HCl], g/dm^3	υ_{Au}, mg/(cm^2·min) at [NaDCC], g/dm^3		
	1	*3*	*5*
0	0.000	0.001	0.051
1.44	0.018	0.022	0.052
7.2	0.034	0.062	0.079
14.4	0.108	0.118	0.101
21.6	0.049	0.085	0.083

maximum rate was achieved at [HCl] = 14.4 g/dm^3 and [NaDCC] = 3 g/dm^3.

We attribute the intensification of gold dissolution at [HCl] = 1.44÷14.4 g/dm^3 to the increased concentration of chloride ions, which act as complexing agents. The subsequent decline in dissolution rate at [HCl] > > 14.4 g/dm^3 may indicate reduced stability of HClO and its non-productive decomposition to Cl_2 with volatilization, as well as surface passivation by intermediate species.

Conclusions

It was established that aqueous NaDCC solutions exhibit high redox potential due to the release of hypochlorous acid during dissolution, while the addition of hydrochloric acid accelerates NaDCC dissolution and promotes the evolution of gaseous chlorine.

1. At [HCl] = 1÷5 g/dm^3, the NaDCC dissolution rate is lower than in pure water, which is attributed to the formation of dichloroisocyanuric acid.

2. Increasing the hydrochloric acid concentration enhances the NaDCC dissolution rate, reaching ~4 mg/(cm^2·min) at [HCl] = 30 g/dm^3.

3. Adding HCl to aqueous NaDCC raises solution Eh from 1150 mV at [HCl] = 0 to 1185 mV at [HCl] = = 5 g/dm^3; however, a further increase to 30 g/dm^3 decreases Eh to 1140 mV, owing to decomposition of both NaDCC and hypochlorous acid.

4. At [HCl] = 15 g/dm^3 and T = 25÷70 °C, the NaDCC dissolution rate increased exponentially from 2.81 to 13.61 mg/(cm^2·min).

5. Raising disk rotation speed from 50 to 900 rpm resulted in a linear increase in NaDCC dissolution rate, reflecting enhanced mass transfer at the reaction surface.

6. The maximum gold dissolution rate (υ_{Au} = = 0.118 mg/(cm^2·min)) was observed at [NaDCC] = = 3 g/dm^3 and [HCl] = 14.4 g/dm^3. At higher HCl concentrations, however, dissolution efficiency declined, requiring further investigation.

7. The findings confirm the potential of sodium dichloroisocyanurate combined with hydrochloric acid as an environmentally safer alternative to cyanide systems for processing Au-bearing materials.

References

1. Filippov A.P., Nesterov Yu.V. Redox processes and intensification of metal leaching. Moscow: Publishing house “Ruda i Metally”, 2009. 543 p. (In Russ.).
Филиппов А.П., Нестеров Ю.В. Редокс-процессы и интенсификация выщелачивания металлов. М.: ИД «Руда и Металлы», 2009. 543 с.
2. Barani K., Kogani Y., Nazarian F. Leaching of complex gold ore using a cyanide-glycine solution. *Minerals Engineering.* 2022;180:107475. https://doi.org/10.1016/j.mineng.2022.107475
3. Logsdon M.J., Hagelstein K., Mudder, T.I. The Management of cyanide in gold extraction. Ottawa: International Council on Metals and the Environment, 1999. 40 p.
4. Birich A., Stopic S., Friedrich B. Kinetic investigation and dissolution behavior of cyanide alternative gold leaching reagents. *Scientific Reports.* 2019;9(1):7191. https://doi.org/10.1038/s41598-019-43383-4
5. Hilson G., Monhemius A.J. Alternatives to cyanide in the gold mining industry: what prospects for the future? *Journal of Cleaner Production*. 2006; 14(12-13):1158—1167. https://doi.org/10.1016/j.jclepro.2004.09.005
6. Kholov Kh.I., Sharifboev N.T., Samikhov Sh.R., Dzhurakulov Sh.R., Zarifova M.S. Gold leaching by various solutions, alternative of cyanide and their prospects in the future. *Zhurnal Sibirskogo federal’nogo universiteta. Seriya: Tekhnika i tekhnologii.* 2021;14(4):433—447. (In Russ.). https://doi.org/10.17516/1999-494X-0324
Холов Х. И., Шарифбоев Н. Т., Самихов Ш. Р., Джуракулов Ш.Р., Зарифова М.С. Выщелачивание золота различными растворами, заменители цианида и их перспективы в будущем. *Журнал Сибирского федерального университета. Серия: Техника и технологии.* 2021;14(4):433—447. https://doi.org/10.17516/1999-494X-0324
7. Merck I., O’Neil, Ann Smith. The Merck index: An encyclopedia of chemicals, drugs, and biologicals. 13th ed. NJ: Whitehouse Station, 2001. 2564 p.
8. Vlassopoulos D., Wood S.A., Mucci A. Gold speciation in natural waters: II. The importance of organic complexing—experiments with some simple model ligands. *Geochimica et Cosmochimica Acta.* 1990;54(6):1575—1586. https://doi.org/10.1016/0016-7037(90)90392-X
9. Perea C.G., Restrepo O.J. Use of amino acids for gold dissolution. *Hydrometallurgy.* 2018;177:79—85. https://doi.org/10.1016/j.hydromet.2018.03.002
10. Brown D.H., Smith W.E., Fox P., Sturrock R.D. The reactions of gold (0) with amino acids and the significance

of these reactions in the biochemistry of gold. *Inorganica Chimica Acta*. 1982;67:27—30. https://doi.org/10.1016/S0020-1693(00)85035-5

11. Marsden J., House I. The chemistry of gold extraction. 2nd ed. Littleton, Colorado, USA: Society for Mining, Metallurgy, and Exploration, 2006. 138 p. https://doi.org/10.1007/BF03215543
12. Sadia Ilyas, Jae-chun Lee. Gold metallurgy and the environment. 1st ed. Boca Raton, FL: Environmental Science, Geology, 2018. 232 p.
13. Nam K.S., Jung B.H., An J.W., Ha T.J., Tran T., Kim M.J. Use of chloride—hypochlorite leachants to recover gold from tailing. *International Journal of Mineral Processing*. 2008;86(1-4):131—140. https://doi.org/10.1016/j.minpro.2007.12.003
14. Seisko S., Lampinen M., Aromaa J., Laari A., Koiranen T., Lundström M. Kinetics and mechanisms of gold dissolution by ferric chloride leaching. *Minerals Engineering*. 2018;115:131—141. https://doi.org/10.1016/j.mineng.2017.10.017
15. Pesic B., Sergent R.H. A rotating disk study of gold dissolution by bromine. *JOM*. 1991;43(12):35—37. https://doi.org/10.1007/BF03223146
16. Qi P.H., Hiskey J.B. Dissolution kinetics of gold in iodide solutions. *Hydrometallurgy*. 1991;27(1):47—62. https://doi.org/10.1016/0304-386X(91)90077-Y
17. Ojeda M.W., Perino E., Ruiz M.C. Gold extraction by chlorination using a pyrometallurgical process. *Minerals Engineering*. 2009;22(4):409—411. https://doi.org/10.1016/j.mineng.2008.09.002
18. Dosmukhamedov N., Kaplan V., Zholdasbay E., Argyn A., Kuldeyev E., Koishina G., Tazhiev Y. Chlorination treatment for gold extraction from refractory gold-copper-arsenic-bearing concentrates. *Sustainability*. 2022; 14(17):11019. https://doi.org/10.3390/su141711019
19. Yakoumis I., Panou M., Moschovi A.M., Panias D. Recovery of platinum group metals from spent automotive catalysts: A review. *Cleaner Engineering and Technology*. 2021;3:100112. https://doi.org/10.1016/j.clet.2021.100112
20. Puvvada G.V.K., Sridhar R., Lakshmanan V.I. Chloride metallurgy: PGM recovery and titanium dioxide production. *JOM*. 2003;55(8):38—41. https://doi.org/10.1007/s11837-003-0103-1
21. Baghalha M. Leaching of an oxide gold ore with chloride/hypochlorite solutions. *International Journal of Mineral Processing*. 2007;82(4):178—186. https://doi.org/10.1016/j.minpro.2006.09.001
22. Rinne M., Elomaa H., Seisko S., Lundstrom M. Direct cupric chloride leaching of gold from refractory sulfide ore: process simulation and life cycle assessment. *Mineral Processing and Extractive Metallurgy Review*. 2022;43(5):598—609. https://doi.org/10.1080/08827508.2021.1910510
23. Karppinen A., Seisko S., Nevatalo L., Wilson B.P., Yliniemi K., Lundström M. Gold recovery from cyanidation residue by chloride leaching and carbon adsorption — preliminary results from CICL process. *Hydrometallurgy*. 2024;226:106304. https://doi.org/10.1016/j.hydromet.2024.106304
24. Niu H., Yang H., Tong L. Research on gold leaching of carbonaceous pressure-oxidized gold ore via a highly effective, green and low toxic agent trichloroisocyanuric acid. *Journal of Cleaner Production*. 2023;419: 138062. https://doi.org/10.1016/j.jclepro.2023.138062
25. Feng F., Sun Y., Rui J., Yu L., Liu J., Zhang N., Zhao M., Wei L., Lu C., Zhao J., Zhang Q., Li X. Study of the "oxidation-complexation" coordination composite ionic liquid system for dissolving precious metals. *Applied Sciences*. 2020;10(10):3625. https://doi.org/10.3390/app10103625
26. Kenzhaliyev B., Koizhanova A., Surkova T., Fischer D., Azlan M.N., Atanova O., Magomedov D., Yerdenova M., Abdyldayev N. Extraction of gold from gravity-flotation concentrates via surfactant and oxidation reagents. *Discover Applied Sciences*. 2024;6(11):598. https://doi.org/10.1007/s42452-024-06281-7
27. Kenzhaliyev B.K., Tussupbayev N.K., Abdykirova G.Z., Koizhanova A.K., Fischer D.Y., Baltabekova Z.A., Samenova N.O. Evaluation of the efficiency of using an oxidizer in the leaching process of gold-containing concentrate. *Processes*. 2024;12(5):973. https://doi.org/10.3390/pr12050973
28. Zhang G., Huang Y., Xiong Z., Ge F., Li Y., Tan J., Zha R. Gold recovery from WPCB gold finger using water-soluble organic leaching agent sodium dichloroisocyanurate. *Sustainability*. 2025;17(6):2415. https://doi.org/10.3390/su17062415
29. Wahman D.G., Alexander M.T., Dugan A.G. Chlori-

nated cyanurates in drinking water: Measurement bias, stability, and disinfectant byproduct formation. *AWWA Water Science*. 2019;1(2):e1133. https://doi.org/10.1002/aws2.1133

30. Lobanov V.G., Naumov K.D., Kolmachikhina O.B., Makovskaya O.Yu., Khabibullina R.E., Kolmachikhina E.B. Method of extracting gold from gold-containing raw materials: Patent 2758915 (RF). 2021.
Лобанов В.Г., Наумов К.Д., Колмачихина О.Б., Маковская О.Ю., Хабибулина Р.Э., Колмачихина Э.Б. Способ извлечения золота из золотосодержащего сырья: Патент 2758915 (РФ). 2021.
31. Lobanov V.G., Khabibulina R.E., Kolmachikhina O.B., Makovskaia O.I. Selection of a leaching system for extraction gold from the Byngovskoe deposits ore. *iPolytech Journal*. 2022; 26(4):688—696. (In Russ.). https://doi.org/ 10.21285/1814-3520-2022-4-688-696
Лобанов В. Г., Хабибулина Р. Э., Колмачихина О. Б., Маковская О. Ю. Выбор выщелачивающей системы для извлечения золота из руды месторождения «Быньговское». *iPolytech Journal*. 2022; 26(4):688—696. https://doi.org/ 10.21285/1814-3520-2022-4-688-696
32. Khabibullina R. E., Lobanov V. G. Environmentally friendly technology of gold leaching from man-made raw materials. In: Actual problems of the development of technical sciences. Ekaterinburg: Ministry of Education and Youth Policy of the Sverdlovsk Region, 2021. P. 31–35. (In Russ.).
Хабибулина Р. Э., Лобанов В. Г. Экологически чистая технология выщелачивания золота из техногенного сырья. В сб: *Актуальные проблемы развития технических наук*. Екатеринбург: Министерство образования и молодежной политики Свердловской обл., 2021. С. 31—35
33. Whitney R.P., Vivian J.E. Solubility of chlorine in Water. *Industrial & Engineering Chemistry*. 1941;33(6):741—744. https://doi.org/10.1021/ie50378a014
34. Jacqueline I. Kroschwitz Kirk-Othmer encyclopedia of chemical technology. 5th ed. Wiley-Interscience, 2004. 896 p.

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