FOUNDATIONS OF CHEMICAL RECOVERY OF METALS FROM LEACHING SOLUTIONS THROUGH ELECTRICAL ACTION

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ABSTRACT

Significant reservoirs of non-ferrous, rare, radioactive metals and gold are concentrated in Kazakhstan. The territory of Kazakhstan calculates over 2 thousand fields and gold deposits, including about 200 explored, dozens of abandoned and producing ones. Kazakhstan gold-ore deposits had been forming in different geotectonic conditions generating a huge variety of gold-containing formations (gold-cobalt-copper, gold- molybdenum-copper, gold-tellurium-bismuthic, gold-silver, gold-arsenic) and wide gold associability with sulphides: pyrites, arsenic pyrite, sulphured copper etc. There are 21 gold deposits are under development with overall reservoirs about 1, 2 thousand tons at average content of 4, 76 g/t.

Key words: Chemical recovery of metals, Leaching solutions, Gold deposits, Kazakhstan.

INTRODUCTION

Mined ore processing is associated using complicated technological enrichment and metallurgy processes, defined by high material costs and metal loss upon technological repartition cycles, environment pollution with high-toxic agents and production wastes. Strongly oxidizing conditions are required, specifically ore sweet roasting with consequent cyanidation of roasted products to destruct sulphides and recover gold. Simple ore cyanidation does not give high gold recovery rates. Sweet roasting requires use of expensive equipment and complicated gas treatment facilities for gold and arsenic recovery from a gas phase.

Strengthening of ecological safety requirements towards arsenical gold production and absence of effective, ecologically clean processing technologies restrain from increasing capacities in one of the largest deposits of Kazakhstan – Bakyrchyk. Advance preparation of

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raw materials is required to recover gold from pyritic and arsenic-pyrite ores using alkali metal cyanides. The preparation technology of such ores towards cyanidation was based on nitrogen oxidation resulting large volume sulphur release which significantly decrease gold recovery into solution in cyanidation process[1].

Investigation of sulphide ore oxidation technology and the association of gold

Sulphide ore oxidation technology is associated with high capital and production costs. The biometallurgy is extremely sensitive to temperature, light conditions and bacteria feeding conditions. Under industrial production conditions the required condition can be difficultly provided. Consequently, world gold mining industry recent years actively searches the new technological resolutions of sulphide ores processing.

Resource base study over Kazakhstan gold mining industry has shown, that the main typomorphic elements of majority gold-ore deposits of Kazakhstan are associated with gold are Ag, As, Sb, Pb, Zn, Cu, Bi, Te, Mo, Sn, Co, Hg and other elements. The gold association with sulphides, telluride availability, gold chalcophylity, and an association with arsenic, stibium, lead, bismuth and other elements resist gold recovery. Gold recovery is resisted by frequently occurred minerals` thick films of argentite, arsenic pyrite, galena and ferrous oxides etc. which are extremely hardly destructible. The way the gold is recovered herewith depends on its occurrence form and concentration in ores. All existing methods of precious metal recovery from refractory ores are based on sulphides dissolution.

Sulphides oxidation progresses with a maximal speed at the beginning of the process, sulphides of old geological formations are more stable, than recent, and sulphide solutions oxidize faster than separate minerals. Arsenic-pyrite and pyrite are chemically stable compounds and are resistant to direct leaching by acids and alkalis solutions; their breaking-up becomes possible only with availability of an oxidizer capable to displace their potential to a positive side. To oxidize sulphide minerals as was described above, the sweet roasting (pyrometallurgy) is conducted with consequent hydrometallurgical roasted products` repartition. The roasting process requires expensive roasting ovens and large number of gas treatment facilities. Cyanide technology requires use of high-toxic agent and strict environment requirements pH (0-3) and Eh ($\geq$ + 1000 mV), results to large scale accumulations of cyanide-containing waters, sharp costs growth due to environment safety measures and at that will not ensure required complete gold recovery.
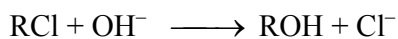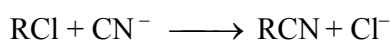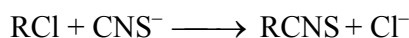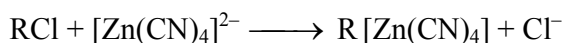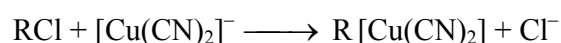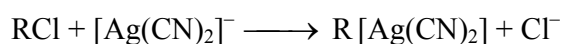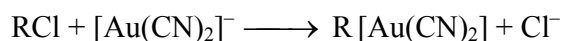
Increasing of cyanidation efficiency is possible both by upgrading the cyanidation process itself, and by advance detachment of big gold fractions from ores within the grinding

cycle. The most successful method of gravity concentrates treatment is their leaching by concentrated cyanide solutions using in the quality of pure oxygen oxidizer.

Under cyanide leaching of preliminary oxidized sulphide ores, the gold solving process is shown as follows:

$$4 \, Au + 8 \, NaCN + 2 \, H_2O + O_2 = 4 \, Na \, [Au \, (CN)_2] + 4 \, NaOH$$
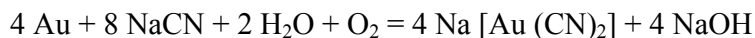
Cyanide water solutions apart from gold, dissolve other metals such as silver, copper, zinc, nickel, cobalt, aluminium, iron. Sorption of precious metals and accompanying mixtures from cyanide solutions flows on reactions:

$$RCl + [Au(CN)_2]^- \longrightarrow R\,[Au(CN)_2] + Cl^-$$

$$RCl + [Ag(CN)_2]^- \longrightarrow R\,[Ag(CN)_2] + Cl^-$$

$$RCl + [Cu(CN)_2]^- \longrightarrow R\,[Cu(CN)_2] + Cl^-$$

$$RCl + [Zn(CN)_4]^{2-} \longrightarrow R\,[Zn(CN)_4] + Cl^-$$

$$RCl + [Fe(CN)_6]^{2-} \longrightarrow R\,[Fe(CN)_6] + Cl^-$$

$$RCl + CNS^- \longrightarrow RCNS + Cl^-$$

$$RCl + CN^- \longrightarrow RCN + Cl^-$$

$$RCl + OH^- \longrightarrow ROH + Cl^-$$

In the result of side reactions flow part of active sorbent groups appear to be engaged by anion mixtures that reduce sorbent capacity over precious metals. From complex cyanide solutions Na [Au (CN)$_2$] the gold is effectively recovered through strongly-based resins, for instance IRA – 400 Amberlite[1].

The processing of gold recovery

For selective gold recovery, in this case, the sorption should be conducted in the presence of organic solvents mixture with mineral acids (for instance, acetone and nitrogen acid). For a gold sorption also effectively applicable semi-functional anions, selectively sorbing gold-cyanide mixture from cyanide solutions as well as complex compound pulps. Electrolytical sorption and electrodesorption can be quite effectively applied. Working with gold-containing ore pulps, the cyanidation efficiency improvement could be expected upon

implementation of countercurrent leaching that would allow to increase metal`s recovery and content in liquid phase.

Search for cyanides replacement should be conducted along with complexing agents in relation to gold, whose system`s stability constants and standard oxidation-reduction potentials are comparable with similar values for cyanide-ions.

(i) Halide–ions, as ligands and adjacent halogen compounds, as oxidizers. Thus known: the family of brome-containing agents, chloration by gaseous chlorine in muriatic media; advance processing by dry chlorine, leganda sodium hypochlorite non-halide, processing in chlorine-containing solution with oxidizer non-halide ($CuCI_2$, $FeCI_3$), processing by pulp hypochlorite over abundant sodium chloride, acidifying of chlorine-containing solution by salt and nitrogen acid, fluoration.

(ii) Sulphourea over various oxidizers (air, oxygen Si (II) – ion, Fe (III) - ion.

(iii) Thiosulphate.

(iv) Thiocyanate with oxidizers.

Increasing effectiveness applying sorption-non-filtration technology of gold recovery from repulped ores should be conducted through the directions: by increasing carbon and resin quality, by improving countercurrent sorption, by implementing pulp flocculants and associated metals, by using pulp electric-ultrasound processing etc. The sulphides are named as hydrosulfuric acid salts and are formed naturally at metal and sulphur compounding. Most of sulphides are occurred under hydrosulfuric affect to water dissolved metal salts.

Gold is in a close association with sulphide minerals. Various sulphides have got various resistances in relation to oxidation processes. Thus Weining and Carpenter locate sulphides in the following row upon descending resistance towards self-induced oxidation: $FeAsS > FeS_2 > CuFeS_2 > ZnS > PbS > Cu_2S$, fahlore. They also have proved that oxidation at the beginning goes in maximal speed that the sulphide of old geological formations is more stable than recent, that the sulphide mixtures oxidize faster than separate minerals. It is proved that between 3 and 12 pH interval sulphides preserve stability[2], and pure pyrite is hardly oxidized.

More easy decomposable sulphides are: pyrrhotine, sphalerite and chalcosine, and the most heavily decomposed are pyrite, argentite, enargite, galenite the rest of sulphides allocated in an intermediate position. Table 1 shows electrode potentials of some sulphide minerals in normal KS1 solution[2].

As shown in the table, the most positive are pyrite, marcasite and copper sulfide; nickel, lead, zinc, molybdenum sulphides belong to relatively negative minerals` group. In this case the discrepancy of potential extreme values of sulphide neutral solutions comprises ~ 450 mV.

Table 1: Static electrode potentials of some sulphide minerals

Mineral	Experiment condition	Mineral potential, mV
1	2	3
Marcasite	24 hours later, in the air	+560
1	2	3
Pyrite	5 days later, along with CO_2	+460, +480
	2-14 days later, over air	+420, +480
	5 days later, over air	+410
	24 hours later, over air	+460, +480
Chalcopyrite	4 days later, over air	+420
	24 hours later, over air	+380, +330
Arsenic pyrite	also	+350
Bornite	-//-	+290, +350
Pyrrhotine	-//-	+300, +340, +255
Pentlandite	-//-	+220
Galenite	-//-	+250, +140, +290, +150
Sphalerite	-//-	+120
Molybdenite	-//-	+140

Electrode potential means the potential jump at the ion media electronic conductor boundary. Current potential jump between the electrodes (mineral) where oxidative-deoxidation reaction takes place, and solution that balances direct and reverse reactions` velocity means electrode potential balance. At balancing, the ion electrochemical potentials` equality is set over the electrode (mineral) and solution:

$$M_i^{o'} + RT\ln a_i' + zF\varphi' = M_i^{o''} + RT\ln a_i'' + zF\varphi''$$

Where, φ' –is a mineral electrode potential; φ'' – is a solution current potential.

From the formula the following is found:

$$\varphi_{a,Me} = \varphi'' - \varphi' = \frac{Mi^{\circ''} - Mi^{\circ'}}{zF} + \frac{RT}{zF} \ln \frac{ai''}{ai'}$$

or

$$\varphi_{a,Me} = \varphi_o' + \frac{RT}{zF} \ln \frac{a'окисл.}{a'восст.}$$

In more traditional view:

$$E = E_o' - \frac{RT}{nF} \ln \frac{aox}{ared}$$

Where E – is metal potential; E_o' – oxidative-recovery potential under oxidizer and deoxidizer activities, equal to a unit; a_{ox} – oxidizer activity; a_{red} - deoxidizer activity.

Sulphides significantly differ from other electron-conducting minerals upon the nature of electric potential`s behavior in oxidative-deoxidation system solutions. In Fe^{2+}/Fe^{3+} system, under pH = 1.6-2.0 for instance, the pyrite starts to take solution oxidative-deoxidation potential under a_{ox} and a_{red} concentrations over 1% .

Takubo researches have proved practically linear pyrite`s potential dependence on solution pH range. Under the free of oxygen solutions the potential gradient per a pH unit comprises 50-60 mV; again in the oxygen atmosphere it varies within 18 up to 48 mV per pH unit, at that in majority cases the values seem to be close to the second range.

For arsenic-pyrite the electrode potential dependence on pH value is also occurs to be practically linear. In concentrated solutions of oxidative-deoxidation systems the sulphides have the potential corresponding system oxidative-deoxidation potential. In these conditions, sulphides` electric potential may be considered as solution oxidative-deoxidation potential.

Polymineral sulphide ores (gold-containing) represent a composite electrode consisting of separate mineral electrodes, having comparatively positive and negative values of electrode potential. Minerals` potential consisting of polymineral ore are significally varies from static minerals` potential represented separately. At that, the system potential becomes dependant on all composing minerals' surface area ratio, their specific resistance, potential-determinative action and polarizing factors and depolarizing effects[1].

Material structure of gold-containing ores is one of the main factors that define gold recovery rates. For instance, gold-containing sulphide ores of Vasilkovsky deposit are represented mainly by silicate minerals: albite ($Na[AlSi_3O_8]$), microcline ($K[AlSi_3O_8]$), quartz (SiO_2), kaolinite ($Al(OH)_8[Si_4O_{10}]$), biotite ($K(MgFe)_3(OH,F)_2[AlSi_3O_{10}]$), hornblende ($Na_3 Fe_3 Fe_2 Si_2 O_{23} (OH)$). Ore minerals composition are arsenic pyrite ($FeAsS$), pyrite (FeS_2), chalcopyrite ($Cu FeS_2$), hematite (Fe_2O_3), bismuthinite (Bi_2S_3), native bismuth (Bi), which are evenly spaced inside quartz reefs. Their gold content comprises 1.5-4 g/t.

Bestobe deposit ores ("Kazakhaltyn" JSC) are related to gold-quartz and gold-sulphide formation. Main ore minerals are – pyrite, arsenic-pyrite, antimony glance; secondary – galenite, scheelite, sphalerite. The major portion of gold and silver is presented in the form of an electrum native alloy (Table 2). The data is shown in the Table 2, achieved by crystal-optical and microreontgenspectral analysis method.

Crystal-optical and microreontgenspectral analysis confirm gold and silver content in arsenic-pyrite ore of Bestobe deposit in the form of native electrum alloy, contenting up to 91% of gold and 10% of silver. Electrum fineness upon gold mass comprises 885 ppm, the rest 115 ppm generally accounts for silver. The other chalcophylic elements – copper, iron, tellurium, selenium are contained in centesimal percent rate.

Small amounts of silver and gold in the copper-ferriferrous alloy, but this formation is very rare met in an ore, taken further for electrochemical gold recovery, and that`s why cannot be considered as the precious metal source for electrochemical process.

Native copper, represented in the ore is a gold and silver carrier.

Precious metals` base mass in ore consisting of gold and silver native alloy is represented in electrum, which gold fineness comprises 885 ppm and 115 ppm of silver. Electrum extractions are sized from the first micron up to 160-180 mym. The wide range of alloy dispersity may inflict difficulties under solutions` analytical monitoring over gold and silver content, as well as affect on their recovery ratio in the time of ore processing by electrochemical recovery method using sodium salt. Upto 20-30 mg/L of gold may pass into solution under electrochemical leaching process of gold. Gold recovery (80-87%) under electrochemical process will allow reduce several times consumption of deficient and expensive cyanide or sulphourea solvents being used during traditional processing methods of such ore.

Gold content in arsenic-pyrite ore of Bestobe deposit is defined by electrum alloy with other sulphide minerals.

Table 2: Bestobe deposit`s component ore minerals

Mineral	Mineral crystal formula	Gold and silver carrier
Pyrite	$(Fe_{0,98}\ Cu_{0,04})_{1,02}$ $(S_{2,00}\ As_{0,001}\ Bi_{0,O04})_{2,05}$	Does not a gold carrier. The silver is detected at specific level
Chalcopyrite	$(Cu_{0,93}Ag_{0,001}\ Au_{0,001})_{0,932}$ $(Fe_{0.79}\ Cd_{0.001}\ Zn_{0,001})_{0,952}$ $(S_{2,00}As_{0,001}Se_{0,001}\ Bi_{0,002})_{2.002}$	Small amount of gold and silver mixes copper, but chalcopyrite cannot be considered as the gold and silver carrier
Arsenic-pyrite	$(Fe_{0,976}Cu_{0,001}Au_{0,001}Ag_{0,001}Mn_{0,001})_{0,980}$ $(As_{0,754}Bi_{0,001}3B_{0,001})_{0,756}$ $(S_{1,00}Se_{0,002})_{1.002}$	Only individual generations contain the gold and silver. The silver is in grains where gold is absent. Arsenic-pyrite cannot be considered as precious metals` carrier
Pyrrhotine	$(Fe_{0,86}\ Au_{0,001}Ag_{0,001}Mn_{0,001})_{0,863}$ $(S_{1,00}As_{0,002}Bi_{0,001}\ Te_{0,001})_{1.004}$	Interrelations of gold, silver, bismuth and tellurium as well as in the arsenic-pyrite. Pyrrhotine is not the gold and silver carrier
Sphalerite	$(Zn_{0,92}Fe_{0,040}Ag_{0,001}\ Fig_{0,001}$ $Mn_{0,001})_{0,962}\ (S_{1,00}As_{0,001})_{1,001}$	Silver is settled, but sphalerite is not the gold and silver carrier
Covelline	$(Cu_{0,977}\ Fe_{0,378}\ Cd_{0,001}Pb_{0,003}Zn_{0,110})_{1,469}$ $(S_{1,00}As_{0,010}Sb_{0,001}Te_{0,001}\ Bi_{0,002})_{0,014}$	Covelline is not the gold and silver carrier
Tetrahedrite (binyte)	$(Cu_{9,55}\ Fe_{0,79}Ag_{0,06}Mn_{0,001}Zn_{1,10})_{11.501}$ $(Sb_{4,40}As_{0,30}\ S_{13,0}$	The silver carrier
Native copper	$Cu_{98;27}\ Fe_{1,50}\ S_{0,05}Ag_{0,01}$ $Au_{0,01}Mп_{0,04}Zn_{0,04}Bi_{0,01}$	Is the gold carrier
Iron turnings	$Fe_{96,86}Ag_{0,05}Cu_{1,98}\ Sb_{0,01}Mn_{0,11}$ $Pb_{0,006}Te_{0,03}\ Zn_{0,68}Bi_{0,03}\ S_{0,01}$	The gold in alloy is not detected on the specific level. The silver in the level of % centesimal
Electrum	$Au_{0,812}Ag_{0,172}\ Cu_{0,001}Fe_{0,002}Bi_{0,005}S_{0,007}$	The majority part of gold and silver are represented in the form of electrum native alloy. Under crystal lattice, per 812 gold atoms fall 172 silver atoms. Admixtures totally take 11th position per each thousand atoms

Mineral	Mineral crystal formula	Gold and silver carrier
Argentite	Ag	Singular grains. Minor distribution does notafford ground for considering it as the silver carrier
Miargyrite	Ag Sb S_2	Contain up to 60% of silver under stoichiometry. Is the silver carrier

Having studied ore component minerals it is fair to say that the pyrite generally does not contain gold; chalcopyrite, arsenic-pyrite and pyrrhotine contain gold but in small amounts. The same can be said about silver content of these minerals. The main gold content is located in the electrum (up to 91%). This fact should be taken into account at its electrochemical recovery. Binyte-antimonious copper sulphosalt contains upto 0.8% of silver and it can be related to silver collector.

As shown from the given example the gold-containing ores of one or another deposit are differ by mineral forms and by golden mineralization nature variety. Presence of fine-ingrained gold mineralization in the ore-forming sulphide minerals significantly increases gold opening-up persistence. As a rule, sulphide ores have sharply showed gold chalcophylity. Chemical affinity with a sulphur leads to a gold concentration in sulphide crystal lattices. Arsenic and stibium stand out as the witnesses of dominance. Fine-ingrained gold is disengaged quite effectively under mineral sweet roasting. Fine shot with evident chalcophylity, over sulphur minerals, stibium, arsenic, lead, tellurids etc. significantly increases gold-containing raw persistence towards solvents. To oxidize minerals and to disengage the gold it is required to have enough strong oxidizing conditions with environment high oxidizing potential.

Studying of an issue regarding increase gold recovery effectiveness from sulphide ores has shown that in principle the assigned task can be resolved applying free of cyanide electrochemical method using the cheapest and available agent-sodium salt. Electrochemical leaching technology of gold over persistent sulphide ores can be an alternative to the existing cyanide technology.

For the purpose of radical technological operation cuts under electrochemical gold recovery technology the following process flow diagram was designed and tested against gold sedimentation on a carbon-fiber cathode.

It was intended, that in case of carbon-fiber use as the cathode the gold will be concentrating on it, and further processing will be narrowed to the gold-containing cathode

processing by means of its roasting, dissolving formed ashes in chloroazotic acid and sodium sulfite gold sedimenting from solution. It was intended, that the process flow diagram will be short-cut on account of excluding such operations as resin screening and its slits washing, resin regeneration in two stages – the first by sulphuric acid mixed solution, and then $3 \div 5\%$ of sulphourea solution in the sulphuric acid solution, resin washing from desorbing solution[2].

Gold recovery from electrochemical leaching solutions

The process flow diagram of gold recovery from electrochemical leaching solutions along with a precipitation on the carbon-fiber cathode (Fig. 1).

- Electrochemical leaching of gold from sulphide-containing pulp with simultaneous gold precipitation on the carbon-fiber cathode (NAT – 100 fiber);

- Directing of free of ash pulp towards thickening;

- Directing of thickened product to the tailing storage;

- Directing of thickener overflow to repeated NaCl solution preparation;

- Removal of gold-contained carbon-fiber from the cathode, its drying and roasting;

- Dissolving of a gold-containing bottom in chloroazotic acid;

- The bottom filtration and washing;

- The bottom dilution and filtration;

- Directing of the filtrate towards gold precipitation by means of Na_2SO_3 solution;

- The bottom filtration and directing to roasting;

- HNO_3 washing, filtration and directing of the gold bottom to a fusion.

The preliminary assessment of carbon-fiber sorption capacity was conducted on the solution, which had been prepared dissolving 100 mg of gold portion in 50 cm^3 chloroazotic acid. The derived solution was diluted with 25% of NaCl solution to 1 dm^3, and then this solution was divided into two parts by 0.5 dm^3 and was poured into glasses. The tested samples of carbon-fiber at the size of 20 x 20 x 5 mm (weight 0.016 and 0.015 g) were mixed in each glass. High-frequency current was supplied into each glass (V = 3V, anodic current density = 800A/m^2, current frequency 800 Hz). Solutions in both glasses were mixed

by magnetic mixer. The gold concentration change was recorded in every two hours. Test results are shown in the Table 3.

Given data in the table is testifying about carbon-fiber high gold capacity, specifically at electric influence, thus certainly confirms correct option selection of gold sedimentation on carbon-fiber cathode.
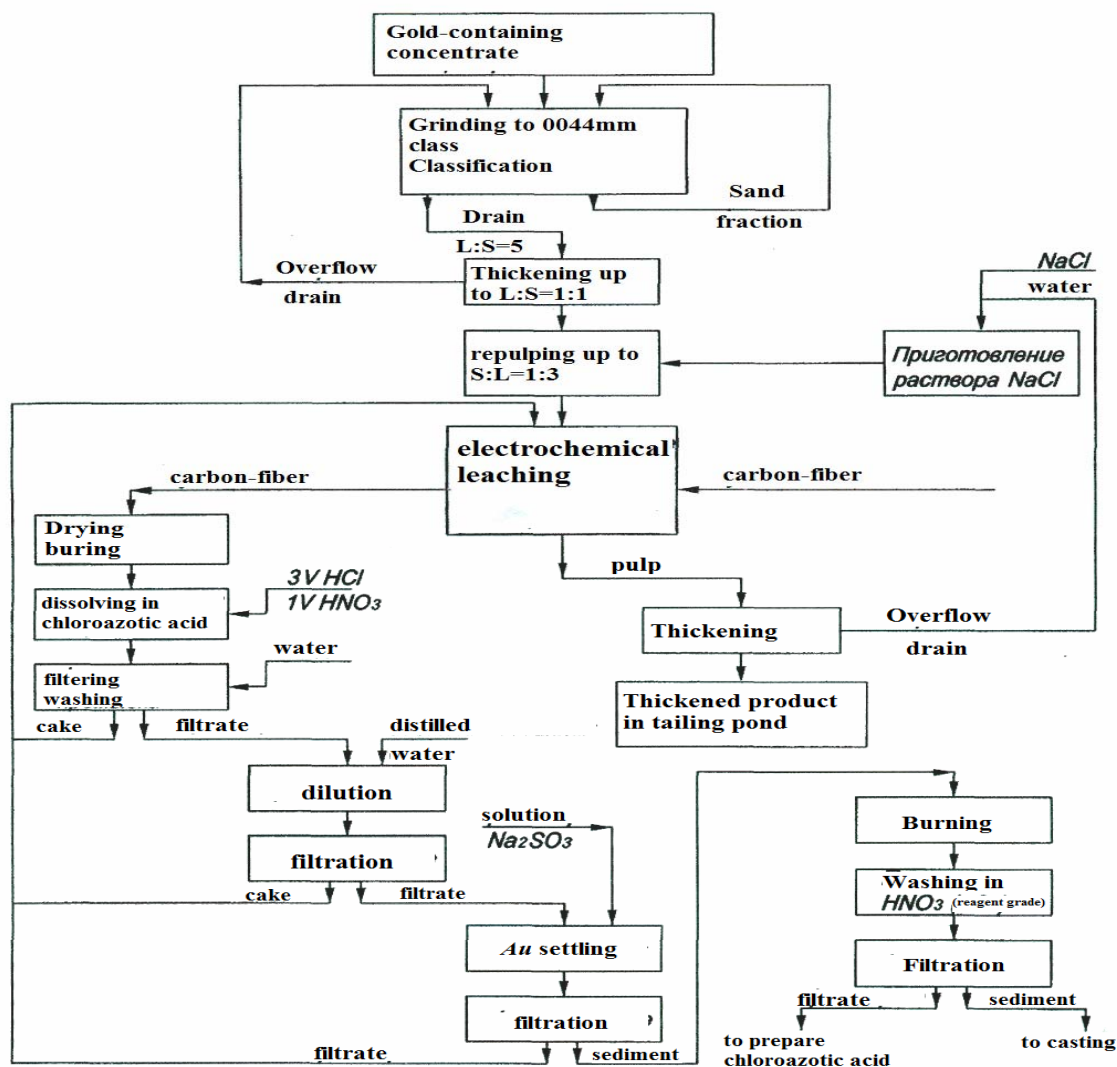

Fig. 1: Process flow diagram of gold recovery from electrochemical leaching solutions with settling on the carbon-fiber cathode

Table 3: Dependence of the carbon-fiber gold capacity on contact duration

Glass No.	Load mass (g)	Gold content in solution (mg/dm)				Carbon-fiber capacity (mg/g)	Notes
		Gold content in solution (mg/dm)					
		0	2	4	6		
1	0.016	56.48	31.7	29.1	30.1	836.2	Without electric influence
2	0.015	56.48	9.55	7.30	5.8	1716.0	With electric influence

To assess capability of achieving discharged gold contents in pulp after electrochemical leaching the gold sorption isothermal curves were derived per carbon-fiber NAT_100 type by means of various concentration, for which the standardized test solutions were prepared containing gold concentration from 0.05 mg/dm^3 upto 50 mg/dm^3, cooking salt – 250 mg/dm^3. Isothermal curves were taken both with and without supplying a high frequency current.

Current parameters:

-Frequency - 800 Hz;

-Anodic current density - 800 a/m^2;

Sorption process duration - 2 hours.

Under the current effect the sorption isothermal curve (top chemisorption) has yet more convex formation, at that, the gold adsorbent capacity`s dependence on its balanced concentration represents vertically rising line. That points at possibility of organization gold electric sorption process in one – two stages along achieving minimal (< 0.02 mg/dm^3) discharged gold concentrations in pulp liquid state. Before moving to semi-industrial experiments, the laboratory experiments had been conducted over simulation of two-stage electrochemical leaching process using carbon-fiber electric sorption. The laboratory agitator was fabricated for the purpose of two-stage leaching shown in Fig. 2.

The graphite rod was used in the quality of anode with the size of 10 x 15 mm, in the quality of cathode – stainless steel plate wound with carbon-fiber. The carbon-fiber`s weight was 0.02 g. The carbon-fiber was wound with single layer of fiberglass and was fixed with fiberglass thread.

Live parts were tightly wound with insulation thread. The dual-chamber agitator` geometric capacity comprises 1.5 dm^3. The working capacity taking into account aeration

comprises 0.99 dm^3. The pre-made pulp was ground up to 0.044 mm sulphide concentrate class, mixed in the ratio of S : L = 1 : 3 with NaCl solution concentration - 250 g/dm^3, the pulp was fed to anode part of one of the chamber, and from the other chamber`s anode part the spent pulp was taken to analysis. Pulp feeding was conducted discretely in every 0.25 hour in the capacity of 0.03 dm^3, thus the leaching duration comprised ~ 8 hours. The electrical leaching was conducted in the ratio of S : L = 1 : 3, C_{NaCl} – 250 g/dm^3, by anodic current density 800-1000 A/m^2, 4-6 voltage, 0.2-0.5 A current strength.
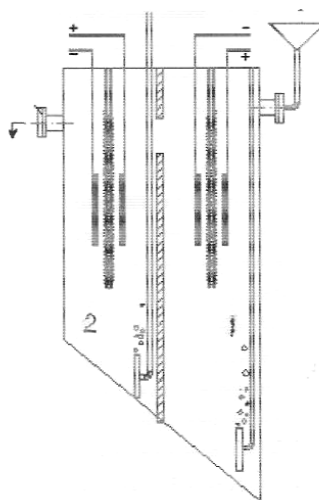
Fig. 2: The agitator for two-stage gold precipitation electrical leaching on carbon-fiber cathode

Table 4 shows average results upon three tests of the bench-top experiment over two-stage electrochemical leaching and gold electrical sorption on carbon-fiber cathode.

Table 4: Experiment results

No.	Time (h)		1	2	3	4	5	6	7	8
Stage 1	Residual gold content over phases	solid, g/t	-	17.2	-	-	18.3	-	-	-
		liquid, mg/dm^3	-	7.1	8.2	-	3.7	-	2.3	3.0
Stage 2	Residual gold content over phases	solid, g/t	6.3	5.2	6.9	6.9	6.4	7.5	5.3	6.3
		liquid, mg/dm^3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Recovery, %		88.8	90.8	87.8	87.8	88.6	86.7	90.6	88.8

According to the conducted bench-top research results, the combination of electrochemical leaching with carbon-fiber cathode electric-sorption will allow to obtain high level gold recovery.

On the basis of research and experiment results the semi-industrial technological examinations were conducted over manufactured unit in "Reactive" LLP scientific and production center. In order to conduct the examination, the gold-containing raw was used amounting 11.0 g/t of gold content representing gravity preparation tails of sulphide ores, presented to "Altyn-Aliance - 3" LLP in the amount of 5.5 t for examination in "Reactive" LLP scientific and production center under condition that the refined gold to be returned.

The equipment chart (Fig. 3) was formed to conduct semi-industrial tests of the technology, including two consequently installed electrochemical equipments.
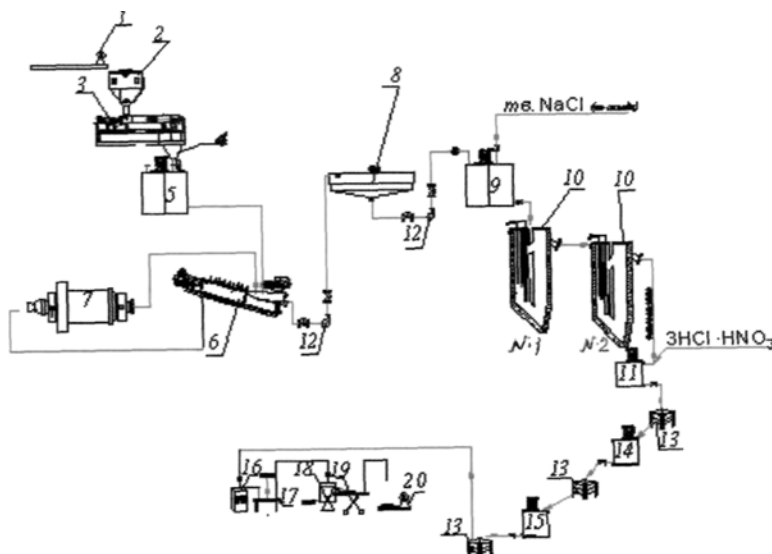
1 –Weights; 2 –Feeder; 3 –Auger feeder; 4 –Chute; 5 –Conditioning tank; 6 –Classifier; 7 –Mill; 8 –Thickener; 9 –Repulpator; 10 –Electric sorption leaching apparatus; 11 –Reactor; 12 –Pump; 13 –Nutsch filter; 14 –Settlement pond; 15 –Precipitator; 16 –Calcination oven; 17 –Reclaimer table; 18 –Bullion furnace; 19 –Casting form; 20 –Laboratory weights.

Fig. 3: Equipment chart of gold electrochemical leaching with precipitation on carbon-fiber cathode

Graphite is used in the quality of anode in the electrochemical units. Any conductive is acceptable to make a cathode, but the cover is made of carbon-fiber material, protected with a layer of nonreactive porous material, for instance filtering fiberglass. The assignment

of filtering fiber – first of all to protect carbon-fiber from mechanical damages which should not be mechanically destructed, because in this case significant gold losses may occur; secondly, filtering fiber prevents solid particles from penetration into carbon-fiber. In the same time, high porosity of carbon-fiber and filtering baffle ensures dissolved gold`s free access towards cathode.

When defining electrodes` dimensions, it was proceeded from necessity of supplying first of all anodic current density over 800 A/m^2, as well as current specific power consumption. Current supply to carbon-fiber (NAT-100) was implemented through graphite frame, on which primarily carbon-fiber was wound and then – fiberglass.

Semi-industrial tests of the technology were conducted in the following operation condition:

- NaCl concentration – 200-250 g/dm^3;

- Pulp density – 0.33 Kg/dm^3;

- S : L ratio = 1 : 3;

- Electrolyte voltage – 6-12 BV;

- Anodic current density – 800-1000 A/m^2;

- Electro-processing duration – 8 hours.

While testing, the gold recovery parameters were recorded upon collected samples over 4,6 and 8 hours during unit operation. There were totally 12 experiments, spent over 5146 kg of sulphide raw. Sulphides` content (pyrite, arsenic-pyrite) in the raw material comprised 21.2%. The main load was taken upon unit #1 under electrochemical gold recovery into solution. The carbon-fiber cathode of the unit had adsorbed in average 76% of gold. Gold pre-recovery up to 90-92% level was performed by the unit #2. The technology test results are introduced in Table 5. According to the test results, the gold concentration in liquid phase of tail pulp at the unit #2 output comprises 0.02-0.03 mg/dm^3 that indicates carbon-fiber cathode`s high efficiency. Raising electrolysis voltage from 6 up to 12V and anodic current density from 800 up to 1000 A/m^2 significantly increased gold recovery. Raising NaCl concentration also increases electrochemical process efficiency.

During sorption process, cathode traveled to pulp countercurrent. Gold-saturated cathode was washed from silts, got free of protective cover (fiberglass), and then carbon-fiber was removed from the frame and was burnt in a muffle furnace. A gold-containing leach was dissolved in 30% nitric acid and was filtered off. Settlings on the filter were burnt

again in the muffle furnace, and then were dissolved in 100 g chloroazotic acid under condition: τ = 1 hour, t = 60 ÷ 70°C. The solution had been filtered, and the sediment was washed in 100c^3 distilled water, a filtrate and a wash-water were combined and coffee-like gold sediment was settling down by adding 50 g of sodium sulfite into the combined solution, which was burnt in the muffle furnace at the temperature of 870°C. Achieved golden color cake was washed once again in specific sort of nitric acid, and then through melting on gas burner we received gold alloy which was studied for base material content. Study results – 99.9% of gold.

Table 5: The results of semi-industrial tests of gold electric-sorption on the cathode (carbon-fiber)

Test No.	Measuring time, hour	Processed		First unit			Second unit			Total gold recovered (%)
		Ores (t)	Pulps (m³)	Gold recovered (%)	Residue in cake (g/t)	Residue in solution mg/dm³	Gold recovered (%)	Residue in cake (g/t)	Residue in solution, mg/dm³	
NaCl – 20%, J – 800A/м², V – 6B										
Average testing		0.426	1.275	65.0	3.85	0.09	11.6	2.57	0.03	76.6
NaCl – 25%, J – 800A/м², V – 12B										
Average testing		0.425	1.276	76.4	2.59		7.83	1.73	0.02	84.3
NaCl – 25%, J – 1000A/м², V – 12B										
Average testing		0.434	1.302	87.3	1.39		4.2	0.93	> 0.02	91.6

Generally, summarizing the results of semi-industrial experiments, it can be stated that the created combination diagram of electrochemical leaching and carbon-fiber material electric-sorption processes is efficient and can be widely implemented in industrial practice having quite high economical benefit[2].

CONCLUSION

Kazakhstan gold-ore deposits had been forming in different geotectonic conditions generating a huge variety of gold-containing formations (gold-cobalt-copper, gold-molybdenum-copper, gold-tellurium-bismuthic, gold-silver, gold- arsenic) and wide gold associability with sulphides: pyrites, arsenic pyrite, sulphured copper etc. There are 21 gold deposits are under development with overall reservoirs about 1.2 thousand tons at average content of 4.76 g/t.

For selective gold recovery, in this case, the sorption should be conducted in the presence of organic solvents mixture with mineral acids (for instance, acetone and nitrogen acid). For a gold sorption also effectively applicable semi-functional anions, selectively sorbing gold-cyanide mixture from cyanide solutions as well as complex compound pulps. Electrolytical sorption and electrodesorption can be quite effectively applied. Working with gold-containing ore pulps, the cyanidation efficiency improvement could be expected upon implementation of countercurrent leaching that would allow to increase metal`s recovery and content in liquid phase.

Material structure of gold-containing ores is one of the main factors that define gold recovery rates. For instance, gold-containing sulphide ores of Vasilkovsky deposit are represented mainly by silicate minerals: albite ($Na[AlSi_3O_8]$), microcline ($K[AlSi_3O_8]$), quartz (SiO_2), kaolinite ($Al(OH)_8[Si_4O_{10}]$), biotite ($K(MgFe)_3(OH,F)_2[AlSi_3O_{10}]$), hornblende ($Na_3 Fe_3 Fe_2Si_2O_{23}$ (OH)). Ore minerals composition are arsenic pyrite (FeAsS), pyrite (FeS_2), chalcopyrite ($CuFeS_2$), hematite (Fe_2O_3), bismuthinite (Bi_2S_3), native bismuth (Bi), which are evenly spaced inside quartz reefs. Their gold content comprises 1.5-4 g/t.

Summarizing the results of semi-industrial experiments, it can be stated that the created combination diagram of electrochemical leaching and carbon-fiber material electric-sorption processes is efficient and can be widely implemented in industrial practice having quite high economical benefit.

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