Improving gold extraction and economic efficiency by testing intensive leaching processes

Ikromjon Boboev[1]*, *Khilola* Salieva[1], *Madina* Abdulloeva[1], *Nigina* Sharipova[2], *Zarrina* Abdulloeva[1], and *Akbarjon* Haqdodov[1]

[1]Dushanbe branch of National University of Science and Technology "MISIS", Nazarshoeva Steet, 7, Dushanbe, 734042, Tajikistan
[2]MSU Branch in Dushanbe, Bohtar Street, 35/1, Dushanbe, 734003, Tajikistan

Abstract. In this paper the possibility of existing methods of intensification of the cyanidation process of gold-bearing raw materials of nonrefractory type was considered: cyanidation with the supply of oxygen or air during the process and with the use of water pre-saturated with dissolved oxygen. When using air in the process of cyanidation with the supply of water pre-saturated with oxygen, the recovery of gold at the level of 83.9% was achieved at a duration of 16 hours and was the most effective. The research revealed a surprising phenomenon related to the low rate of decrease in dissolved oxygen concentration, which does not follow Guerney's law. At the transition from distilled to mineralized (recycled) water, the rate of oxygenation increases while deoxygenation decreases. Preservation of oxygen in the pulp volume gives the possibility to further intensify the cyanidation process.

1 Introduction

Oxidation of metallic gold by oxygen to gold (I) or gold (III) ions is impossible in the region of conditions under which water is stable. The high values of the standard reduction potentials of Au(I) and Au(III) to metallic gold, 1.83 and 1.52 V, respectively, indicate that both ions are unstable and strong oxidizing agents; if they are dissolved, water will decompose to the O_2 and metallic gold will precipitate. Dissolution of gold by oxidation can only be achieved in the presence of a complexing agent such as cyan-ion CN^-, with the formation of a complex $Au(CN)_2^-$, that remains in solution [1-6].

The role of oxygen in the system Au-CN can be described as an electrochemical process in which anodic and cathodic reactions take place:

$$\text{anodic: } 4Au + 8CN^- = 4Au(CN)_2^- + 4e^- \tag{1}$$

$$\text{cathode: } O_2 + 2H_2O + 4e^- = 4OH^- \tag{2}$$

---

* Corresponding author: boboevi@misis.ru

If reactions on the metal surface proceed rapidly, diffusion is the limiting stage CN^- and/or O_2, at that diffusion currents are proportional to the concentration of reactants in the solution volume. In formulas (1) and (2) the dissolution rate of gold R_{Au} two times less than the rate of cyanide consumption R_{CN} and four times the rate of oxygen consumption R_{02}, thus [1, 4, 6]:

$$R_{Au} = R_{CN}/2 = D_{CN}\cdot[CN^-]/2d \text{ and } R_{Au} = R_{02}\cdot 4 = \cdot 4\cdot\ D_{02}\cdot[O_2]/d \qquad (3)$$

where D_{CN} and D_{02} are diffusion coefficients of cyanide and oxygen, respectively;
$[CN^-]$ and $[0_2]$ represent volumetric concentrations of cyanide and oxygen;
d dnotes thickness of the diffusion layer on the gold surface.
In steady state operations:

$$D_{CN}\cdot[CN^-]/D_{02}\cdot[O_2] = 8 \qquad (4)$$

At room temperature the ratio D_{02}/D_{CN} is equal to 1.5, so that the ratio of reactant concentrations in the solution volume reaches the limiting value:

$$[CN^-]/[O_2] = 12 \qquad (5)$$

Habashi proposed another equation, also electrochemical in nature, to describe the dissolution of gold [1, 4]:

$$2Au + 4NaCN + O_2 + 2H_2O \rightarrow 2NaAu(CN)_2 + 2NaOH + H_2O_2 \qquad (6)$$

In response to. (6) R_{Au} half again R_{CN}, but only twice as much R_{02}, so that under steady-state conditions and at the same value of D_{02}/D_{CN}, as above, the limiting ratio is equal to:

$$[CN^-]/[O_2] = 6 \qquad (7)$$

The experimental range (Figure 1) of this ratio is 4.6-7.4, which agrees well with equation (7). Figure 1 shows that if the ratio is greater than the limiting value, the reaction is controlled by diffusion O_2, and at lower values, by diffusion CN^-.

In practice, it is easier to maintain high cyanide levels than high dissolved oxygen levels in solution, mainly if air rather than oxygen is used. As a consequence, most plants operate at cyanide levels, so gold dissolution is always dependent on dissolved oxygen concentration.

Work on intensification of the cyanidation process by increasing the concentration of dissolved oxygen was first carried out in the 70-ies of the last century by the outstanding Soviet scientist Plaksin V.I. His works established that this can be achieved by the following methods: cyanidation by supplying cyanide solutions pre-saturated with oxygen, cyanidation by supplying oxygen, cyanidation in autoclaves under oxygen pressure, pre-aeration of the pulp with oxygen followed by cyanidations [5, 7-11]. The latter method can be associated not so much with intensification of the cyanidation process as with suppression of cyanized minerals [9, 10]. For instance, non-resistant ores are processed by direct cyanidation. During this process, some sulfide minerals, in particular iron sulfides, react with cyanide, which leads to additional consumption of reagent [8, 10]. Therefore, the use of the latter process minimizes the additional consumption by partially oxidizing the sulfide minerals prior to cyanidation. Similar results were also obtained in other works [1-3].

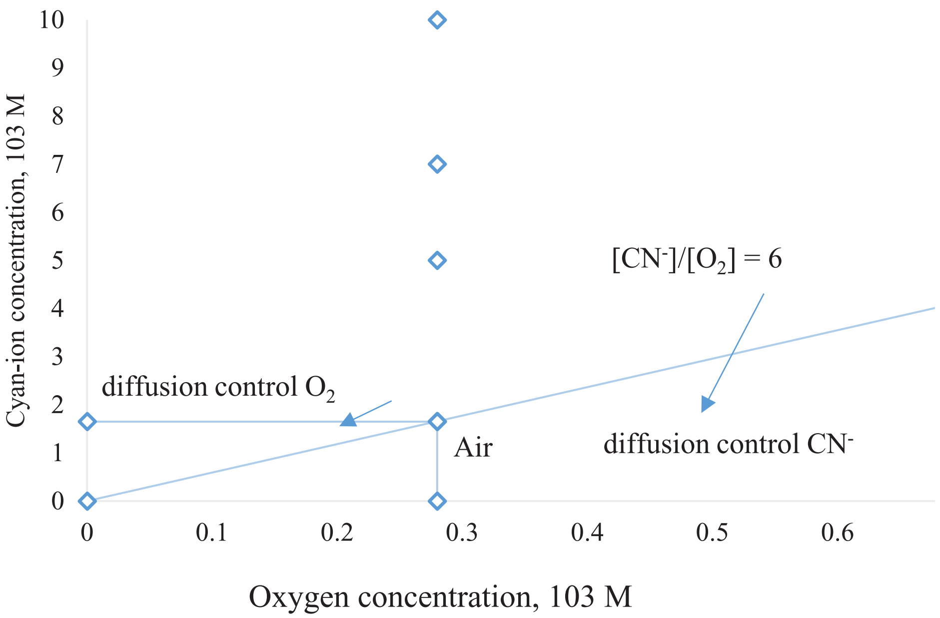

Fig. 1. Diffusion control for the oxygen-cyanide system.

In addition to pressure and temperature, the equilibrium state of dissolved oxygen concentration is also influenced by the mineralization of the solution, which in the case of slurry can include, in addition to salt ions, also density and viscosity with the increase of which the equilibrium concentration decreases. For this reason, in direct cyanidation and cyanidation with the use of pre-saturated oxygenated water in the autoclave, the concentration of dissolved oxygen decreases to 3.7 mg/l.

In this work, research on the intensification of the cyanidation process by existing methods was carried out on a sample of non-refractory tailings with gold content at the 2.4 g/t.

2 Materials and research methods

Materials. Ore samples of overlying tailings were selected for testing, in which ore mineralization is represented predominantly by quartz, feldspars and clay minerals. The valuable main component of the sample is gold, which content reaches 2.4 g/t. Iron, copper, lead and zinc sulfides are contained in negligible amounts.

Leaching. In all experiments the L:T ratio was kept at the level of 3:2, pH of the environment was created by the slaked lime and amounted to 10.5, the temperature was at the level of 25 °C, cyanide concentration was maintained at 400 ppm, cyanidation duration was 24 hours.

An agitation agitator was used for leaching.

Leaching with a constant supply of oxygen or air was conducted in a tank equipped with a porous titanium disk aerator Matala.

Preliminary oxygenation of water. The parameters of the waters used for research are presented in Table 1.

Table 1. Main parameters of water used for testing.

Water	pH	Concentration, mg/l		
		O_2	Organic compounds	$Ca^{2+}/Mg^{2+}/Na^{+}$
Distilled	6.1	8.12	<0.25	unexamined
Technical	8.3	7.51	2.7	54/12/71
Reverse	9.4	5.13	61	394/87/538

Autoclave and porous titanium disk aerators Matala with micropore size 200 µm were used for preliminary oxygenation of water.

By supplying pure oxygen using distilled water, the oxygen concentration in the autoclave was brought to 37 mg/L in 4.6 min. Aeration was carried out at a duration of 20 min with dissolved oxygen concentration reaching 25 mg/L.

Oxygen or air was supplied to the tank equipped with an aerator at the rate of 4 m^3/hour. This high rate of oxygen supply is due to the formation of smaller bubbles for efficient dissolution of gases.

3 Results and discussion

The results in Table 2 show that the gold dissolution rate using aerators with constant supply of both air and oxygen is much higher than cyanidation using preoxygenated water in the autoclave, which is clearly demonstrated in Figure 2. The concentration at 37 mg/L is shown prior to dilution with the sample sample. During the dilution process, the concentration drops sharply. It can be concluded that this option of intensification of the cyanidation process makes it possible only for a short time to replenish the lack of dissolved oxygen.

Table 2. Results of cyanidation kinetics of gold-bearing overburden dumps.

No.	Duration, hour	Output, %	Concentration Au, mg/L	Table of Contents Au in kiln, g/t	Extraction Au, %
I Direct cyanidation					
1	4	99.97	0.78	1.23	48.7
2	8	99.95	0.95	0.97	59.4
3	12	99.94	1.09	0.74	68.3
4	16	99.87	1.19	0.61	74.5
5	20	99.88	1.24	0.54	77.3
6	**24**	**99.87**	**1.28**	**0.48**	80.1
II Cyanide leaching using pre-oxygenated water in an autoclave					
1	4	99.89	0.87	1.09	54.6
2	8	99.87	1.05	0.82	65.8
3	12	99.85	1.19	0.62	74.3
4	16	99.86	1.27	0.49	79.5
5	20	99.87	1.31	0.44	81.7
6	**24**	**99.86**	**1.32**	**0.41**	**82.8**
III Cyanide leaching using pre-oxygenated water using an aerator					
1	4	99.75	1.03	0.86	64.3
2	8	99.64	1.13	0.71	70.6
3	12	98.61	1.22	0.56	76.5
4	**16**	**99.55**	**1.31**	**0.42**	**82.4**
5	20	99.52	1.25	0.37	84.6
6	24	99.51	1.25	0.36	84.8
IV Cyanide leaching with constant air supply using an aerator					
1	4	99.86	0.91	1.03	57.1
2	8	99.82	1.14	0.68	71.6
3	12	98.78	1.22	0.54	77.4
4	**16**	**99.78**	**1.33**	**0.39**	**83.9**
5	20	99.76	1.36	0.36	85.2
6	24	99.75	1.37	0.33	86.1
V Cyanide leaching with constant oxygen supply using an aerator					
1	4	99.81	0.85	1.12	58.3
2	8	99.76	1.06	0.81	66.4
3	**12**	**98.72**	**1.34**	**0.38**	**84.1**
4	16	99.72	1.38	0.33	86.2
5	20	99.71	1.38	0.33	86.3
6	24	99.70	1.38	0.32	86.5

It should be noted the advantage of the initial dissolution rate in cyanide leaching using pre-saturated oxygenated water with the use of an aerator (see Figure 2). The decrease in oxygen concentration (using an aerator) is slow, dropping from 24.7 to 12.7 mg/L in 4 hours, while with pre-saturation autoclave, a decrease in oxygen concentration from 36.7 to 3.7 mg/L after pulp dilution was observed in the first 12 minutes. The oxygen concentration during pre-saturation after pulp dilution stabilized at 7.9-8.5 mg/L in 8 hours. These observations were surprising.

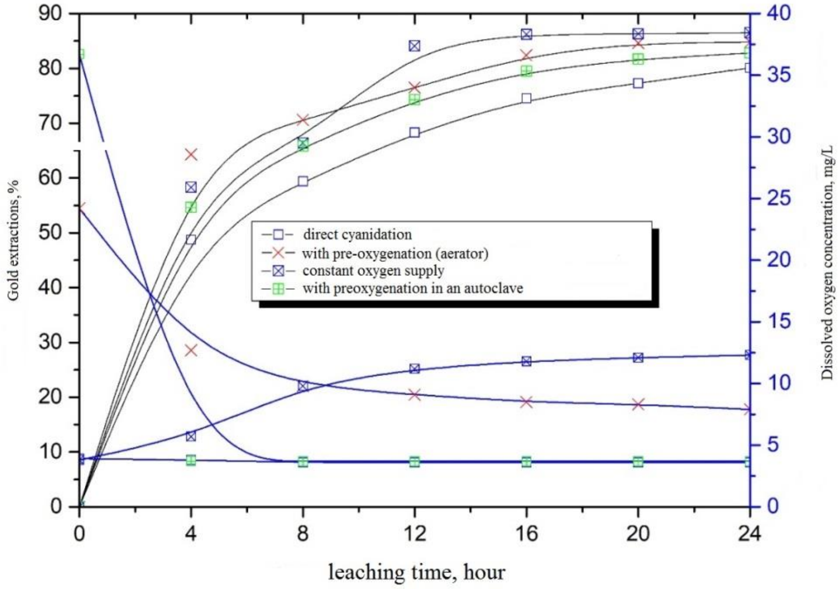

Fig. 2. Dependence of gold recovery and dissolved oxygen concentration on leaching duration.

Autoclave saturation confirms the fact that pre-saturation of water with oxygen for further use in the cyanidation process does not have a significant effect, as it is completely subject to Henry's law. This is due to the fact that after the solution leaves the autoclave dissolved oxygen is rapidly released into the atmosphere, as a result of which the concentration of oxidizer in the solution falls sharply. The secretion occurs due to the fact that the partial pressure of oxygen above the solution falls sharply (to atmospheric pressure). As a consequence, dissolved oxygen tends to its equilibrium concentration corresponding to the given value of pressure (normal pressure) and other physical and chemical properties of the created medium. For this reason, autoclave saturation has not found its application. As for the cyanidation process, carried out with a constant supply of pure oxygen, despite the positive results, its application requires high oxygen consumption. This negatively affects the cost of gold. At the same time, it should be noted that a surprising phenomenon has been discovered, related to the behavior of dissolved oxygen after saturation using an aerator with a scheme with preoxygenation. For instance, during pre-saturation (Figure 3), the dissolved oxygen concentration rose to a level of 24.7 mg/L in 14 minutes as part of the distilled water that was used for cyanidation. But when fed into the cyanidation process, the concentration of dissolved oxygen together with falling to the normal value (3.8 mg / L) at the initial stage of the process (as was the case with the autoclave), on the contrary remains at a sufficiently high level that we at this stage it was attributed to the behavior of bubbles.

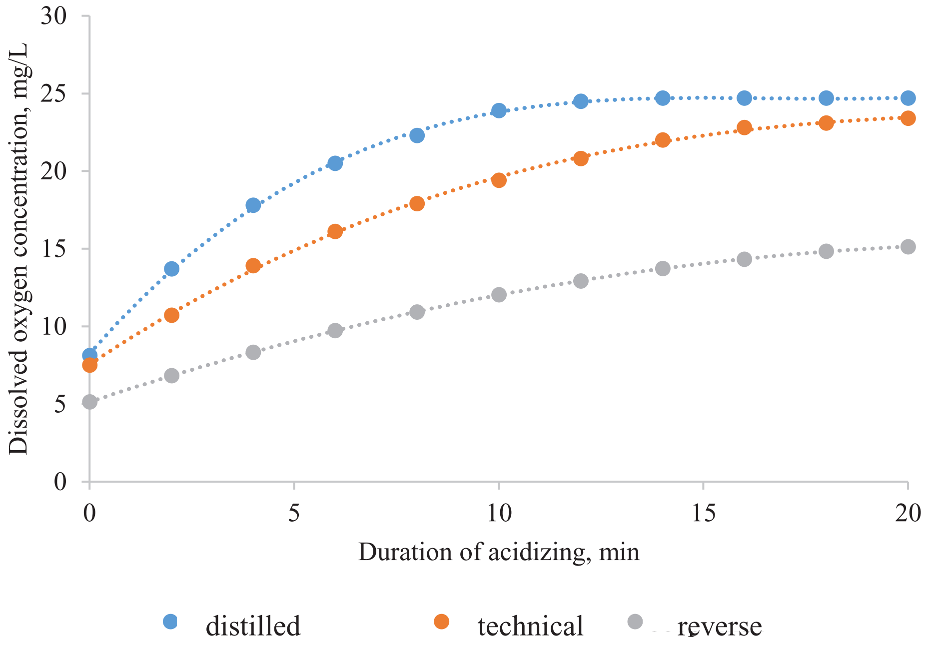

Fig. 3. Dependence of solutions acidification degree on duration.

It was assumed that the difference in the degrees of oxygen saturation between different waters (Figure 3) was due to the negative effect of contamination of process and recycled water with organic matter and salt ions - $Ca^{2+}/Mg^{2+}/Na^{+}$.

A technical and economic comparison of the main indicators for calculating the cost of processing one ton of the studied raw materials was made. The cost of 1 gram of gold, depending on its content and the degree of persistence of the raw material, the conditions of the region, the technology of mining and processing and the policy of the company itself can reach 42-43 $ / gram. However, taking into account the fact that the tested raw material is not refractory, the profitability of a gram of gold by conventional technology was considered equal to 22 $ per gram with a theoretical recovery of 100%. The detailed calculation is presented in Table 3.

Table 3. Comparative calculation of gold production cost.

Method	Extraction, %	Time, hour	Cost of 1 g Au, $				
			in view a.c.*, $/г Au	additional costs (a.c.)			
				total a.c. converted to 1 g Au, $	c including, $/t:		
					O_2, $/t	Autoclave	Aerator and compressor (12 kWt)
I	80.1	24	22/0.80 = **27.5**	-	-	-	-
II	82.8	24	(22+8.42)/0.83 = **36.7**	(4.8+15.4)/2.4 = 8.42	$6m^3/t*0.8\$/m^3 = 4.8$	15.4	-
III	82.4	16	(22+4.5)/0.82/1,5 = **21.4**	(9.6+1.3)/2.4 = 4.5	$12m^3/t*0.8\$/t = 9.6$	-	1.3
IV	83.9	16	(22+2.2)/0.84/1,5 = **19.3**	5.4/2.4 = 2.25	-	-	5.4
V	84.1	12	(22+32.6)/0.841/2 = **32.5**	(74.4+4.0)/2.4=32.6	$93m^3/t*0.8\$/m^3 = 74.4$	-	4.0

Cost of electricity – 0.028 $/kWt, and oxygen – 0.8 $/m^3. The duration of pre-aeration by method III was 4 hours.
* Adjusted for duration.

The calculation showed the advantage of method IV - cyanide leaching at constant air supply with the use of aerator, which achieves the lowest cost at the level of 19.3 $/g Au. At an average throughput of 800,000 tons/year, the cost benefit, excluding the increase in annual throughput due to reduced duration, is $11 202816 compared to Method I - Direct Cyanidation.

4 Conclusions

1. Using air, the cyanidation process with pre-saturated oxygenated water with a gold recovery of 84.1% and a duration of 12 hours proved to be the most efficient process.
2. The research revealed a surprising phenomenon related to the low rate of dissolved oxygen concentration drop not corresponding to Gerny's law. At transition from distilled to mineralized (recycled) water the rate of deoxygenation decreases. Preservation of oxygen in the pulp volume will give possibility to further intensify the cyanidation process

References

1. N. Hedley, H. Tabachnick, Chemistry of Cyanidation, Technical Report. No. 23 (American Cyanamid Co., Wayne, NJ, 1968)
2. V. S. T. Ciminelli, K. Osseo-Asare, Metall Mater Trans **B 26**, 209–218 (1995) DOI: https://doi.org/10.1007/BF02660961
3. R. G. Bautista, JOM **38**, 47–49 (1986) DOI: https://doi.org/10.1007/BF03258715.
4. J. O. Marsden, C. L. House, Gold Bulletin **39(3)**, 138-138 (2006) DOI:10.1007/BF03215543
5. H. Schmidbaur, H. G. Raubenheimer, Angew. Chem. Int. Ed. **59(35)**, 14748-14771 (2020) DOI: 10.1002/anie.201916255
6. Jü. Lorösch, Process and Environmental Chemistry of Cyanidation (Degussa AG, Frankfurt am Main, 2001)
7. A. D. Bas, E. Ghali, Y. Choi, Hydrometallurgy **172**, 30-44 (2017) DOI:10.1016/j.hydromet.2017.06.021
8. B. Surimbayev, A. Akcil, L. Bolotova, et al., Miner. Process. Extr. Metall. Rev., 1-19 (2023) DOI: 10.1080/08827508.2023.2230344
9. Q. Zhong, Y. Yang, L. Chen, et al., Metals **8 (1)**, 80 (2018) DOI:10.3390/met8010080
10. L. Lorenzen, J. S. J. Van Deventer, Hydrometallurgy **30(1–3)**, 177-193 (1992) DOI:10.1016/0304-386X(92)90083-C
11. M. I. Jeffrey, P. L. Breuer, Miner. Eng. **13 (10–11)**, 1097-1106 (2000) DOI:10.1016/S0892-6875(00)00093-5