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Fundamentals for optimization of cyanide processes in flotation

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ABSTRACT

Theoretical substantiation of activation, deactivation and depression processes in flotation of copper-pyrite, copper-zinc and polymetallic ores with the use of cyanide as well as their regularities are considered. Physico-chemical models derived for various cyanide processes in flotation and automatic control systems of principal elaborated for regulation of selective flotation of ores and bulk concentrates with cyanide are recommended to the use at the mineral processing plants for optimization of cyanide processes, improvement of technological indices, cutting down the cyanide consumption and conditioning of recycle waters to prevent environmental pollution. © 2004 SDU. All rights reserved.

Keywords: Cyanide; Mineral processing; Flotation; Automation systems

1. INTRODUCTION

Main disadvantages of cyanide technology of sulphide ores flotation are the contamination of sewage with toxic substances and loses of gold and silver (up to 4-8%) by dissolution in tailings. Despite of these drawbacks cyanides are indispensable and they are extensively used in both the selective flotation of sulphide ores containing nonferrous metals and in a following separation of concentrates received (Abramov, 1983).

Significant cyanide consumptions create both ecological and technological problems. It is conditioned by the necessity of compensation for wide changes in ore compositions. The latter is usually correlated with wide changes in xanthate (38-126mg/l), cyanide (350-1600mg/l) and copper-cyanide (140-900mg/l) ion concentrations as well as with pH values (9.5-11.8) in the pulp. It was observed, for example, in the lead-copper separation circuit at "Belousovskaya" (Kazakhstan) and "Zyryanovskaya" (Kazakhstan) plants (Abramov, 1983).

The aim of this work is to investigate and theoretically analyze different possibilities for optimization of cyanide processes in flotation of ores of non-ferrous metals aiming at cutting down of the cyanide consumption.

2. PHYSICO-CHEMICAL MODELS OF FLOTATION OF SULPHIDE MINERALS

Physico-chemical models of flotation discussed here (Abramov, 1978) are theoretically and experimentally proved quantitative relationships between concentrations of reagents in the pulp at the boundary conditions for flotation or depression of minerals to be recovered or depressed.

Flotation of sulphide minerals from ores is carried out with the use of sulphydril collectors, among which xanthates (X^-) are the basic type. Values of their concentration in the pulp necessary for the complete or maximal recovery of copper and iron sulphides in the absence of cyanide are described by physico-chemical models (Abramov, 1978; 1993) for chalcocite (Eq. 1), covellite (Eq. 2), bornite (Eq. 3), chalcopyrite (Eq. 4), pyrite (Eq. 5), marcasite (Eq. 6), pyrrhotite (Eq. 7):

$$\lg[X^-] = \{-16.43 + (3/2)(E^0_{CuX}/0.059) - (1/2)\lg[CuOH^+][X^-]\} + (5/4)pH - (1/8)\lg[S_2O_3^{2-}] \tag{1}$$

$$\lg[X^-] = \{-13.97 + (4/3)(E^0_{CuX}/0.059) - (1/3)\lg[CuOH^+][X^-]\} + (4/3)pH + (1/6)\lg[S_2O_3^{2-}] \tag{2}$$

$$\lg[X^-] = \{+1.07 + (5/21)\lg[Cu^+][X^-] + (16/21)\lg[FeOH^+][X^-]\} + (17/21)pH + (2/21)\lg[S_2O_3^{2-}] \tag{3}$$

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$$lg[X^-] = \{+0.96 + (1/13)lg[Cu^+][X^-] + (12/13)lg[FeOH^+][X^-]\} + (9/13)pH + (2/13)lg[SO_3^{2-}] \qquad (4)$$
$$lg[X^-] = \{-0.29 + lg[FeOH^+][X^-]\} + (5/7)pH + (1/7)lg[S_2O_3^{2-}] \qquad (5)$$
$$lg[X^-] = \{-0.51 + lg[FeOH^+][X^-]\} + (5/7)pH + (1/7)lg[S_2O_3^{2-}] \qquad (6)$$
$$lg[X^-] = \{-1.98 + lg[FeOH^+][X^-]\} + (4/5)pH + (1/10)lg[S_2O_3^{2-}] \qquad (7)$$

where the product $[MeOH^+][X^-] = K$ is different for different minerals. It is determined by the nature of a mineral and also by conditions for maintaining of the required dixanthogen concentration ($[X_2]$) in the near-electrode layer of the mineral to be floated (Abramov, 1978; 1993). For ethyl xanthate the value of the product $[MeOH^+][X^-]$ is equal to: -24.50 for chalcocite; -22.50 for covellite; -13.20 for bornite; -11.53 for chalcopyrite; -10.46 for pyrite; -10.66 for marcasite and -9.85 for pyrrhotite. For butyl xanthate corresponding values of $[MeOH^+][X^-]$ are ten times smaller than those for ethyl xanthate.

A number of possible mechanisms for explaining the depressing action of cyanide on iron and copper sulfides in selective flotation have been previously suggested. Among them are formation of stable metal - cyanide complexes by the selective dissolution of metal xanthates (Janetski et al., 1977; Wang and Forssberg, 1996); adsorption of cyanide or metal - cyanide complexes that render the surface hydrophilic (Wang and Forssberg, 1996); displacement of adsorbed collectors (Leja, 1981); reduction of the pulp redox potential and consumption of oxygen in the pulp inhibiting the chemisorption / oxidation of collector molecules (Carlson and Muir, 1976; Hall et al., 1990) and reactions involving sulphur or polysulphides at the mineral surface with the following formation of hydrophilic thiocyanate (Leja, 1981; Wang and Forssberg, 1996).

Results of a number of investigations (Gaudin, 1957; Abramov, 1978; Bogdanov et al., 1990) suggest that the main reason of cyanide depressing action on flotation of iron sulfides, activated sphalerite and copper sulfides consist not in the cyanide sorption on their surface but in the tying together mineral cations into stable complex cyanide compounds. It decreases the concentration of cations in the liquid phase of pulp to such degree that dixanthogen formation or collector sorption on the mineral surface become impossible at all. This theory is in a good agreement with experimental data on: dissolving of copper by cyanide from the surface of both copper minerals and activated sphalerite (Gaudin, 1957; Abramov, 1978; Bogdanov et al., 1990); correlation of the solubility of heavy metals xanthates in cyanides with depressing action of cyanides on the floatability of corresponding metals (Abramov, 1993).

Addition of cyanide and appearance of cyanide ions (CN^-) in the pulp result both in the formation of iron- and copper cyanide complex ions and in the change of the $MeOH^+$ ions concentration near the sulfides surface. As the $Fe(CN)_6^{4-}$ complex (Osseo-Asare et al., 1984; Wang and Forssberg, 1996) and $Cu(CN)_2^-$ complex (Abramov, 1978; 1993) are the most stable ones, the following Eqs. 8 and 10 are expected to take place:

$$FeOH^+ + 6CN^- + H^+ = Fe(CN)_6^{4-} + H_2O \qquad (8)$$
$$lgK = lg([Fe(CN)_6^{4-}] / [FeOH^+][CN^-][H^+] = 44.50 \qquad (9)$$
$$Cu(CN)_2^- + H_2O = CuOH^+ + 2CN^- + H^+ + e \qquad (10)$$
$$E = 1.793 + 0.059lg[CuOH^+] - 0.059lg[Cu(CN)_2^-] + 0.118 lg[CN] - 0.059pH \qquad (11)$$

Quantitative relationships between concentrations of CN^-, X^-, H^+, $Fe(CN)_6^{4-}$ ions necessary for the complete flotation of pyrite (Eq. 12), marcasite (Eq. 13) and pyrrhotite (Eq. 14) are obtained using both the $[FeOH^+]=f(pH, [S_2O_3^{2-}])$ relationship for each of iron sulphides (Abramov, 1978) and the boundary condition expressed by Eq. 9:

$$lg\{[Fe(CN)_6^{4-}] / [CN^-]^6\} + 2lg[X^-] + (2/7)pH =$$
$$= 44.21 + 2lg[Fe(OH)^+][X^-] + (1/7)lg[S_2O_3^{2-}] = lgK \quad (lgK_f = 20.87; lgK_d = 14.87) \qquad (12)$$
$$lg\{[Fe(CN)_6^{4-}] / [CN^-]^6\} + 2lg[X^-] + (2/7)pH =$$
$$= 43.89 + 2lg[Fe(OH)^+][X^-] + (1/7)lg[S_2O_3^{2-}] = lgK \quad (lgK_f = 20.14; lgK_d = 14.14) \qquad (13)$$
$$lg\{[Fe(CN)_6^{4-}] / [CN^-]^6\} + 2lg[X^-] + (1/4)pH =$$
$$= 42.52 + 2lg[Fe(OH)^+][X^-] + (1/10)lg[S_2O_3^{2-}] = lgK \quad (lgK_f = 20.42; lgK_d = 14.42) \qquad (14)$$

It follows from the latter relationships that smaller concentrations of CN^- ions are required for depression of pyrrhotite compared with pyrite. This conclusion is consistent with results of studies by Osseo-Asare et al. (1984) and Grano et al. (1990). Cyanide decreases the rate and degree of xanthate adsorption on iron sulphides, especially on pyrrhotite, and leads to desorption of xanthate preliminary adsorbed on their surfaces (Prestidge et al., 1993). However, no cyanide species were detected on pyrite (Leppinen et al., 1995) and other iron sulphides (Bogdanov et al., 1990) at cyanide concentrations (consumptions) used in practice.

The analogous relationships for conditions of the complete flotation of chalcocite (Eq. 15), covellite (Eq. 16), bornite (Eq. 17), and chalcopyrite (Eq. 18) are obtained using the relationship $[CuOH^+]=f(pH, [S_2O_3^{2-}])$ for chalcocite, covellite, bornite, the relationship $[CuOH^+]=f(pH, [SO_3^{2-}])$ for chalcopyrite (Abramov, 1993) and expression for the potential E given in Eq. 11:

$$lg\{[Cu(CN)_2^-] / [CN^-]^2\} + (2/3) lg[X^-] + (1/6) pH =$$
$$= 19.60 + (2/3) lg[Cu(OH)^+][X^-] - (1/12) lg[S_2O_3^{2-}] = lgK \quad (lgK_f = 2.85; lgK_d = 0.85) \qquad (15)$$
$$lg\{[Cu(CN)_2^-] / [CN^-]^2\} + (3/4) lg[X^-] =$$
$$= 20.10 + (3/4) lg[Cu(OH)^+][X^-] - (1/8) lg[S_2O_3^{2-}] = lgK \quad (lgK_f = 2.87; lgK_d = 0.72) \qquad (16)$$

$$lg\{[Cu(CN)_2^-]/[CN^-]^2\} + (16/21)lg[X^-] + (1/21)pH =$$
$$= 20.37 + (16/21)lg[Cu(OH)^+][X^-] - (16/21)lg[S_2O_3^{2-}] = lgK \quad (lgK_f = 2.46; lgK_d = 0.10) \tag{17}$$
$$lg\{[Cu(CN)_2^-]/[CN^-]^2\} + (12/13)lg[X^-] - (3/13)pH =$$
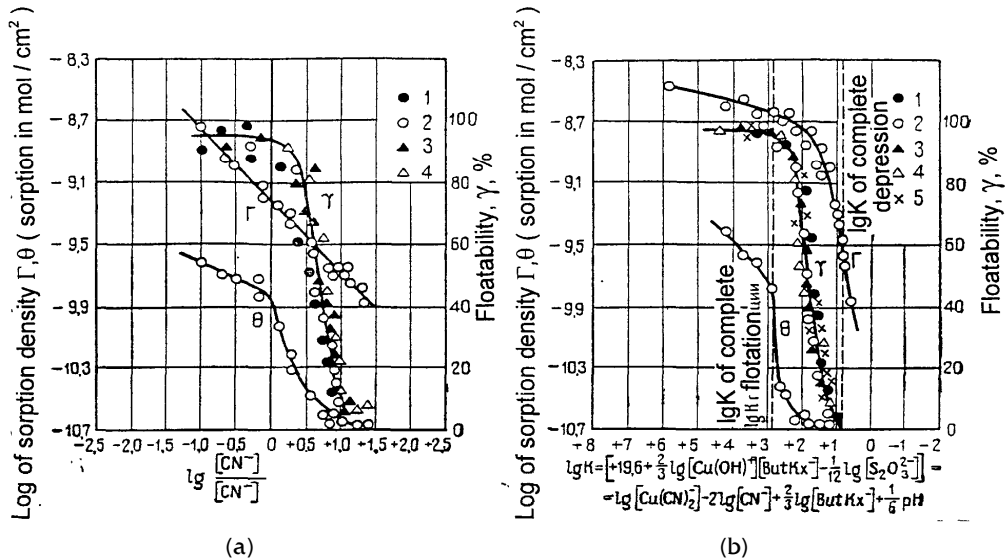$$= 20.45 + (12/13)lg[Cu(OH)^+][X^-] - (2/13)lg[S_2O_3^{2-}] = lgK \quad (lgK_f = 0.51; lgK_d = -2.30) \tag{18}$$

Figure 1. Effect of the quotient of the available ($[CN^-]_a$) and critical ($[CN^-]_c$) concentrations of cyanide ions (left) and lgK value (right) on the floatability (γ) of Zyryanovsk pyrite (a) and Dzhezkazgan chalcocite (b), sorption density of «chemically» attached collector (Γ) and physically sorbed dixanthogen (θ) on their surface at various concentrations of butyl-xanthate in the pulp (in mol/l): 1- 5.33x10^{-5}; 2- 1.33x10^{-4}; 3- 2.66x10^{-4}; 4- 5.33x10^{-4}

Values for K_f (flotation) and K_d (depression of flotation) are given for butyl xanthate. They are ten times higher, if ethyl xanthate is used.

The value of the product $[Me(OH)^+][X^-]$ at the boundary condition for the complete depression of copper and iron sulphides in the presence of cyanide ions is lower by a factor of 3 compared with its value at the boundary condition for the complete flotation of the above-mentioned minerals. Conditions for the complete (maximal) flotation of copper and iron sulphides are bound with the formation of dixanthogen in the sorption layer. As expected, the complete depression of flotation is correlated with the absence of dixanthogen in the sorption layer in spite of the substantial sorption density of the "chemically" attached collector at these conditions (Figure 1). The change in the adsorption density of xanthate and dixanthogen on the pyrite surface as a function of the cyanide concentration is in a good agreement with the results of previous studies of Prestige *et al.* (1993).

As can be seen from the above discussion, the physico-chemical models for flotation and depression of iron sulphides in the presence of cyanide in the pulp given by Eqs. 15–18 can be used for optimization of cyanide processes in flotation of ores of nonferrous metals.

3. PROCESSING OF COPPER-PYRITE ORES

Selective flotation of copper sulphides from copper-pyrite ores is curried out usually at depression of iron sulphides by lime. However, in the presence of "sootish" formations of secondary copper sulfides or oxide copper minerals in the ore, it is practically impossible to secure the complete depression of pyrite even in the strong - alkaline medium (pH~12) created by lime. The part of pyrite, even if activated by copper ions negligibly, will float with copper sulfides at any pH value. An increase in selectivity of iron and copper sulfides flotation in this case and in the case when the part of iron sulfides is represented by arsenopyrite (not sufficiently well depressing in the lime medium) is reached by the use of cyanide (Abramov, 1983).

3.1. Influence of physico-chemical parameters of the cyanide system on the copper and iron sulphides separation

Eqs. 12-18 show that, in the general case, the cyanide concentration in the pulp necessary for depression of various iron and copper sulfides depends on the ratio of concentrations of xanthate, hydrogen, sulphoxide ions and the metal-cyanide complex. These equations permit also to evaluate influence of pH values, xanthate and $Cu(CN)_2^-$ ions concentrations on the excess and deficiency of cyanide in the pulp and floatability of iron and copper sulfide under border conditions for chalcopyrite flotation. Results of such evaluation are shown in Figure 2 and permit to claim the following:

- the increase in pH under conditions of the critical for chalcopyrite cyanide ions concentration brings to the decrease in the excess of cyanide in the pulp as compared with its critical concentration for iron sulfides (Figure 2a, curves 4-6). At these conditions copper and iron sulfides flotation properties are drawing together (Figure 2a). It is precisely this fact, which explains that flotation of copper-pyrite ores at plants is carried out with cyanide at minimum alkalinity of the pulp (pH<9) usually created by small additions of sodium carbonate;
- the increase in the xanthate ions concentration in the pulp at the border conditions of chalcopyrite flotation (Eq. 18) brings to the increase in the surplus of cyanide concentration for iron sulfides, to an improvement of their depression in flotation (Figure 2b) and to the rise in selectivity of copper and iron sulfides separation in flotation;
- the analogous regularity is observed at the increase in $Cu(CN)_2^-$ ions concentration in the pulp (Figure 2c). The high concentration of soluble copper salts in the pulp is characteristic for copper-pyrite ores, the considerable part of copper in which is represented by fine-disseminated secondary copper sulphides formations. In this case cyanide is used more often (Abramov, 1983).
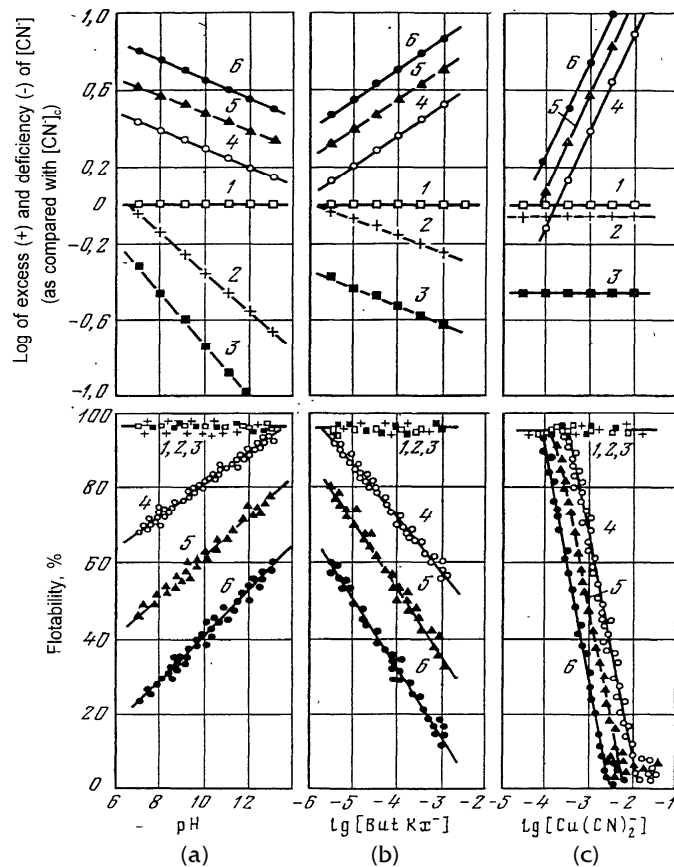

Figure 2. Effect of pH (a), concentrations of butyl-xanthate (b) and $Cu(CN)_2^-$ ions (c) on the excess (+) and deficiency (-) of cyanide in the pulp as compared with its critical concentration and on the floatability of covellite (2), bornite (3), pyrrhotite (4), marcasite (5) and pyrite (6) in bordering conditions for chalcopyrite (1) flotation at constant conditions: a- $[ButX^-]=10^{-4}$mol/l, $[Cu(CN)_2^-]=10^{-3}$mol/l; b- pH 8, $[Cu(CN)_2^-]=10^{-3}$mol/l; c- pH 8, $[ButX^-]=10^{-4}$mol/l

3.2. The use of the buffering cyanide system for depression of iron sulphides flotation

Concentrations of cyanide ions causing the depression of iron sulfides flotation are not large. To secure the sufficient cyanide concentration in the liquid phase of the pulp under conditions of considerable changes in the mineral composition and consuming ability of ores, reagent conditions based on formation in the pulp volume of such compounds as zinc and iron cyanides are used. The latter cyanides are the suppliers of cyanide ions in accordance with their solubility products at these conditions. If there are already zinc or ferrous salts in the pulp, then only cyanide is added. If they are absent, the mixture of cyanide is used either with zinc (at the most plants) or with iron vitriol (at «Metahambr» plant).

In both cases available [CN⁻] in the pulp is sufficient for depression of iron sulphides but is less than the critical [CN⁻] for copper sulphides flotation (Abramov, 1978; 1983).
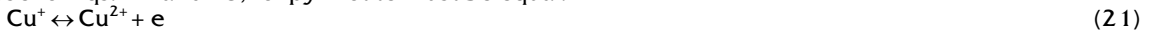
It can be shown that the presence of zinc cyanide $Zn(CN)_2$ in the pulp also prevents iron sulphides activation by copper ions.

If dissolved copper in cyanide additions is precipitated as CuCN, the concentration of cuprous ions can be found on the basis of Eq. 19 according to the Eq. 20:
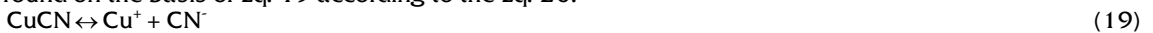
$$CuCN \leftrightarrow Cu^+ + CN^- \tag{19}$$
$$\lg[Cu^+] = -20.00 - \lg[CN^-] \tag{20}$$

The relationship between concentrations of cuprous and cupric ions near the surface of oxidizing pyrite and pyrrhotite can be found taking into account that equilibrium potentials for Eqs. 21 and 23 for pyrite and those for Eqs. 21 and 25, for pyrrhotite must be equal.

$$Cu^+ \leftrightarrow Cu^{2+} + e \tag{21}$$
$$E = +0.153 + 0.059 \lg[Cu^{2+}] - 0.059 \lg[Cu^+] \tag{22}$$
$$FeS_2 + 11H_2O \leftrightarrow Fe(OH)_3 + 2SO_4^{2-} + 19H^+ + 15e \tag{23}$$
$$E = +0.408 - (19/15) 0.059 \, pH + (2/15) 0.059 \lg[SO_4^{2-}] \tag{24}$$
$$FeS + 7H_2O \leftrightarrow Fe(OH)_3 + SO_4^{2-} + 11H^+ + 9e \tag{25}$$
$$E = +0.372 - (11/9) 0.059 \, pH + (1/9) 0.059 \lg[SO_4^2] \tag{26}$$

The necessary relationship between cuprous and cupric ions near the pyrite (Eq. 27) and pyrrhotite (Eq. 28) surface as the function of pH can be obtained by equating the right parts of Eqs. 22 and 24 for pyrite and Eqs. 22 and 26 for pyrrhotite and taking the concentration of sulphoxide ions in the pulp to be equal to 10^{-3} mol/l (Abramov, 1978; 1983):

$$\lg[Cu^{2+}] = 3.93 - (19/15) \, pH + \lg[Cu^+] \tag{27}$$
$$\lg[Cu^{2+}] = 3.38 - (11/9) \, pH + \lg[Cu^+] \tag{28}$$

Therefore, values of $[Cu^{2+}]$ necessary for activation of pyrite and pyrrhotite can be calculated using the fallowing Eqs. 29 and 30 (Abramov, 1978):

$$\lg[Cu^{2+}] = +4.63 - (26/15)pH \tag{29}$$
$$\lg[Cu^{2+}] = -5.40 - (16/9)pH \tag{30}$$

Substituting lg $[Cu^{2+}]$ values from Eqs. 29 and 30 and lg $[Cu^+]$ - from Eq. 20 into Eqs. 27 and 28 the following expressions for the critical concentration of CN⁻ ions ($[CN^-]_c$) can be derived for pyrite (Eq. 31) and pyrrhotite (Eq. 32) respectively:

$$\lg[CN^-]_c = -20.70 + (7/15) \, pH \tag{31}$$
$$\lg[CN^-]_c = -11.22 + (5/9) \, pH \tag{32}$$

Activation both pyrite and pyrrhotite can be prevented when $[CN^-]>[CN^-]_c$.

The available concentration of cyanide ions ($[CN^-]_a$) in the presence of $Zn(CN)_2$ can be calculated on the basis of Eq. 33 according to Eq. 34:

$$Zn(OH)_2 + 2CN^- + 2H^+ \leftrightarrow Zn(CN)_2 + 2H_2O \tag{33}$$
$$\lg[CN^-]_a = -13.30 + pH \tag{34}$$

Analyses on the quotient $[CN^-]_a/[CN^-]_c$ for pyrite (Eq. 35) and pyrrhotite (Eq. 36) shows that their activation by copper salts in the presence of $Zn(CN)_2$ is impossible. This makes the problem of iron sulfides depression in flotation much easier to solve:

$$\lg([CN^-]_a / [CN^-]_c) = 7.40 + (8/15) \, pH \tag{35}$$
$$\lg([CN^-]_a / [CN^-]_c) = -2.08 + (4/9) \, pH \tag{36}$$

3.3. Optimization of cyanide processes in selective flotation of copper-pyrite ores and separation of the bulk concentrates

Selective flotation of ores or separation of the bulk concentrates are carried out in the weakly alkaline (sodium carbonate or lime) medium with cyanide additions (up to 200g/t). pH value in flotation does not exceed 9. Its further increase leads to decrease in cyanide excess in the pulp as compared with its critical concentration for iron sulphides (Eqs. 12-14) and to drawing together of copper and iron sulphides flotation properties (Figure 2a).

The possible schemes of principal for the automatic control and regulation of selective flotation of ores and bulk copper-pyrite concentrates with the use of cyanide are shown in Figure 3.

In Figure 3a, the sodium carbonate or lime consumption in selective flotation of ores is changed by the batch meter 7 in accordance with the signal of the regulator 5 in which current pH values measured by the transducer 2 are compared with the set values (action 8). Consumption of xanthate is regulated by the batch meter 6 driven by the regulator 5 which compares the available $[X^-]$ in the pulp (measured by the transducer 4) with xanthate concentration calculated by the functional control unit 3 according to the relationship $[X^-]=f(pH)$ for chalcopyrite (Eq. 4) with pH values measured by the transducer 2. Cyanide consumption is changed by the batch meter 11 in accordance with the signal of the regulator 5. The latter compares the current lg $([Cu(CN)_2^-]/[CN^-]^2)$ values, which are measured by the transducer 9, with those calculated by the functional control unit 10 according to the relationship $lg([Cu(CN)_2^-]/[CN^-]^2)=f(pH,[X^-])$ for critical conditions of chalcopyrite flotation (Eq. 18).
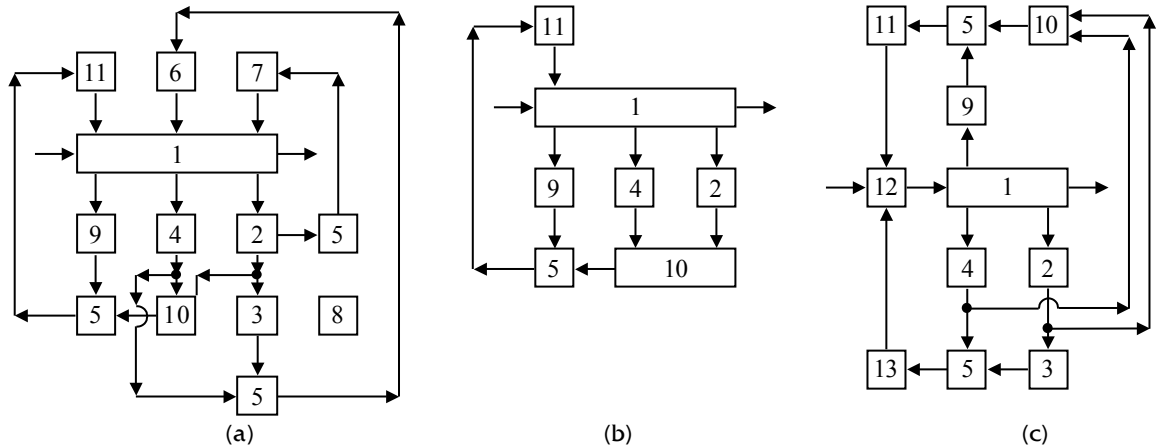

Figure 3. Possible automatic control systems of principal for regulation of the selective flotation of ores and bulk concentrates with cyanide: 1- flotation; 2- pH transducer; 3- functional control unit computing $[X^-]=f(pH)$; 4- transducer measuring the concentration of xanthate ions; 5- regulator; 6- batch meter of xanthate; 7- batch meter of lime or sodium carbonate; 8- setting action; 9- transducer measuring $lg([Cu(CN)^-_2]/[CN^-]^2)$ value; 10- functional control unit computing $lg([Cu(CN)^-_2]/[CN^-]^2)=f(pH, [X^-])$; 11- batch meter of cyanide; 12- vat-mixer; 13- batch meter of the activated carbon.

The second scheme (Figure 3b) can be used in separation of the bulk copper-pyrite concentrates. Cyanide consumption is regulated as in the previous case (Figure 3a). This scheme is the most efficient one when low process selectivity and low quality of copper concentrates are conditioned by the high degree of activation of iron sulphides.

Sometimes the process of the bulk selective flotation and recleaning of the copper concentrate is complicated by the surplus concentration of collector and frother in these operations. In such cases a scheme of the automatic control and regulation system shown in Figure 3c includes a block suitable for removing off their excess by the activated carbon or other absorbents. The control of the absorbent consumption through the batch meter 13 is carried out by the regulator 5 in which the available xanthate concentration, $[X^-]_a$ (the signal of the transducer 4) and its setting value (the exit signal of the functional control unit 3) are compared. Eq. 4 of the minimal xanthate concentration necessary for the complete chalcopyrite flotation is employed as the criterion for the functional control unit 3 working at the condition $[X^-]=f(pH)$. Finally, the function $lg([Cu(CN)_2^-]/[CN^-]^2)=f(pH, [X^-])$ needed for critical conditions of chalcopyrite flotation (Eq. 18), is employed as in the previous case i.e. as the criterion for the regulation system of cyanide consumption.

Applications for such automatic control and regulation systems can permit an increase in the efficiency of bulk and cleaning operations of the selective flotation, improvement of quality of concentrates avoiding a metal recovery diminution and, finally, cutting down of cyanide consumption at plants.

4. PROCESSING OF COPPER-ZINC ORES

In processing of copper-zinc ores, cyanides can either activate or depress zinc sulphides flotation when the composition or/and consuming ability of ores at plants are changing dramatically (Abramov, 1983; Bocharov and Riskin, 1993).

4.1. Reasons for activation of zinc sulphides by copper in the presence of cyanide

If the ratio of concentrations of free cyanide and copper ions in the liquid phase of pulp will be less than 1:1, copper ions precipitate as a mixture of copper cyanide and copper hydroxicarbonate (pH<9), or as copper hydroxide (pH>9). In this case the concentration of monovalent copper ions in solution can be found from Eqs. 19 and 20.

In order to find the relationship between concentrations for mono- and divalent copper near the oxidizing surface of sphalerite it is necessary to consider Eqs. 37 and 21 with corresponding potentials (Eqs. 38 and 22). In equilibrium, the latter are equal. If the concentration of monovalent copper ions is determined by the solubility product of cuprous cyanide, the substitution of the $lg[Cu^+]$ value from Eq. 20 into Eq. 39 permits to find the value of the available concentration of cupric ions near the sphalerite surface (Eq. 40). The concentration of cupric ions necessary for activation of sphalerites (Abramov, 1978) is determined by Eq. 41.

$$2ZnS + 7H_2O = 2Zn(OH)_2 + S_2O_3^{2-} + 10H^+ + 8e \tag{37}$$
$$E = 0.526 - 5/4 \times 0.059pH + 1/8 \times 0.059lg[S_2O_3^{2-}] \tag{38}$$
$$lg[Cu^{2+}] = 5.15 + lg[Cu^+] - 5/4pH \tag{39}$$
$$lg[Cu^{2+}] = -13.85 - lg[CN^-] - 5/4pH \tag{40}$$
$$lg[Cu^{2+}] = +0.70 - 2pH \tag{41}$$
$$lg[CN^-]_c = -14.85 + 3/4pH \tag{42}$$

Then the condition for activation of zinc sulphides by copper cyanide is the equality of the right parts of Eqs. 40 and 41, going rise to the expression for the critical values of cyanide ions concentration $[CN^-]_c$ (Eq. 42). For $[CN^-]>[CN^-]_c$ activation of zinc sulphides is prevented. The concentration of cyanide ions available in solution is limited by the solubility of CuCN that is about 10^{-10} mol/l. Hence, at pH>6, it is always less than the critical one that promotes activation of zinc sulphides at these conditions.

It is possible to show that even at the critical concentration of cyanide ions the oxidation product of zinc sulphide, $Zn(OH)_2$, on the surface of sphalerite will not convert into $Zn(CN)_2$. It follows from the comparison of the right parts of Eq. 42 and Eq. 34 obtained on the basis of reaction (33). The critical concentration of CN^- ions (Eq. 42) at all pH values is less than the one necessary for the passage of zinc hydroxide into zinc cyanide (Eq. 34).

At the ratio of concentrations of free cyanide and copper ions equal to 2:1 the concentration of monovalent copper in the solution can be determined by Eq. 44 obtained on the basis of the reaction given by Eq. 43. In its turn, the available concentration of ions of the divalent copper in solution, can be calculated by Eq. 45 obtained by substituting the expression for $lg[Cu^+]$ from Eq. 44 into Eq. 39. Substituting of $lg[Cu^{2+}]$ from Eq. 45 into Eq. 37 gives rise to Eq. 46, which describes necessary conditions for activation of zinc sulphides in the presence of complex ions $Cu(CN)_2^-$.

$$Cu(CN)_2^- \Leftrightarrow Cu^+ + 2CN^- \tag{43}$$
$$lg[Cu^+] = -21.65 + lg[Cu(CN)_2^-] - 2lg[CN^-] \tag{44}$$
$$lg[Cu^{2+}] = -15.50 + lg[Cu(CN)_2^-] - 2lg[CN^-] - 5/4pH \tag{45}$$
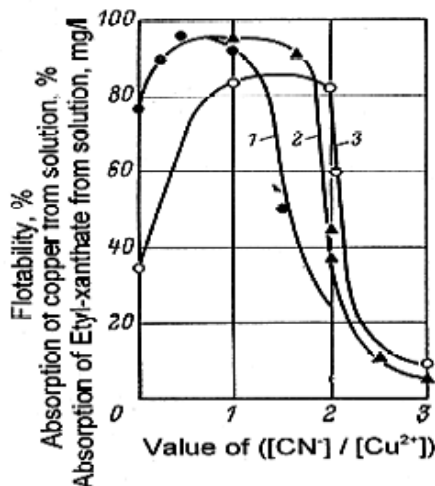$$lg([Cu(CN)_2^-] / [CN^-]^2) = 15.20 - 3/4pH \tag{46}$$

Figure 4. Influence of the quotient of concentrations of cyanide and copper ions on absorption by sphalerite surface from aqueous solution of copper ions (1) [data from Okolovich and Figurkova (1977)], ethyl xanthate (3) [data from Tashiaki (1960-1961)] and floatability of mineral (2) [data from Abramov (1978)]

It is necessary to note that activation ability of the mixture of cyanide and copper, with the ratio 2:1, is rather small. At such ratio, the whole cyanide would be bound in the complex $Cu(CN)_2^-$. Even an insignificant excess of cyanide over this ratio would either prevent a further activation or would cause deactivation of the already activated surface of zinc sulphides and, therefore, would lead to the depression of their flotation. Results of theoretical computations are in a good agreement with experimental data obtained by Tashiaki (1960-1961), Okolovich and Figurkova (1977), and Abramov (1978) see Figure 4.

4.2. Prevention of activation of zinc sulphide minerals and their depression in flotation

A concentration of reagents necessary for prevention of activation of zinc sulphide minerals and their depression in flotation can be estimated on the basis of above mentioned equations. A regime of deactivation or a prevention of activation could be reached by a reduction of concentration of the activating copper ions in the liquid phase of the pulp below the critical concentration required for activation of sphalerite at the given conditions.

For example, if cyanide is used for prevention of activation of zinc sulphides, $[CN^-]$ necessary for this prevention should be not less than $[CN^-]_c$ at the boundary conditions of activation - deactivation described by Eq. 46. Experimental results given in Figure 4 show that exceeding of the ratio of cyanide to copper, 2:1, would break down conditions described by the Eq. 46 and, therefore, would prevent activation and flotation of sphalerite (see curves 1 and 2). Hence, Eq. 46 can be considered as the criterion to the functional control unit of the system for automatic control of conditions preventing activation of zinc sulphides in appropriate circuits of the selective flotation.

Conditions described by Eq. 46 would not cause, at the usual pH values, any depression of flotation of copper sulphides. It could be seen from simple calculations by equating of expressions for $lg([Cu(CN)_2^-]/[CN^-]^2)$ given in Eq. 46 and Eqs. 15-18 describing conditions for complete flotation of copper sulphides in the presence of cyanide ions. Even for chalcopyrite, the critical pH value at $[ButX^-] = 10^{-4}mol/l$ is equal to 12.2; for other copper sulphides it is higher than 13.8.

In practice, cyanide is usually charged together with zinc vitriol at their ratio from 1:10 up to 1:2 (the Sheridan-Griswold regime). In these conditions, a part of loaded reagents will be present in the pulp as precipitates of both cyanide and hydroxide of zinc. The condition of their simultaneous existence is defined on the basis of Eq. 33 by Eq. 34.

A comparison of the available concentration of cyanide ions, $[CN^-]_a$, due to the presence of zinc cyanide (Eq. 34) in the pulp, with the critical concentration, $[CN^-]_c$ at the boundary conditions of sphalerite activation by copper salts (Eq. 46) shows that at pH>5.9 and $[Cu(CN)_2^-]=10^{-3}mol/l$ activation of sphalerite would be impossible (Eq. 47). In turn, substituting of $[CN^-]$ values from Eq. 34 into Eq. 46 one can obtain Eq. 48. This equation shows that, in the presence of zinc cyanide, the concentration of the dissolved copper in the pulp (as $Cu(CN)_2^-$ ions) necessary for activation of sphalerite at the usual conditions of flotation, is hardly achievable.

$$lg([CN^-]_a/[CN^-]_c) = -5.20 - 1/2 lg [Cu(CN)_2^-] + 5/8pH \qquad (47)$$
$$lg[Cu(CN)_2^-]_r = -10.40 + 5/4pH \qquad (48)$$

A possibility for the complete flotation of copper sulphides in the presence of zinc cyanide in the pulp can be evaluated by comparing values of the available concentration of cyanide ions (Eq. 34) with the critical concentration, $[CN^-]_c$, (Eqs. 15-18) that describe conditions of flotation of copper sulphides in the presence of cyanide ions.

Results of computations and experimental researches show (Figure 5) that at accepted conditions ($[Cu(CN)_2^-]=10^{-3}mol/l$ and $[ButX^-]=10^{-4}mol/l$) exceeding of $[CN^-]_a$ over $[CN^-]_c$ and onset of depression of flotation are observed at pH values: 8.7 - for chalcopyrite; 8.8 – 8.9 - for bornite and covellite; 9.3 - for chalcocite. The critical pH values adequate to the onset of depression of copper sulphides flotation grow with increase and are reduced with decrease in concentrations of xanthate and $Cu(CN)_2^-$ ions in the pulp (Figure 6). In flotation of copper-zinc ores, values of $lg[Cu(CN)_2^-]$ and $lg[ButX^-]$ in the liquid phase of pulp are usually changed from −5.0 up to −4.5. Critical pH values calculated for chalcopyrite will be within limits of 7.4 – 7.8 in this case. They coincide completely with pH values 7.4 – 7.7 used in practice (Abramov, 1983; Bocharov and Riskin, 1993). Such pH values are necessary also for improvement of depression of iron sulphides flotation (see Figure 2).

Difficulties in separation of copper and zinc minerals are increased essentially when the significant part of copper in ores is represented by secondary sulphide and oxide minerals causing strong activation of zinc sulphides.

The separation of copper and zinc sulphides in these conditions at plants is usually achieved by the use of a mixture of cyanide with zinc vitriol (Abramov, 1983). Reagent conditions accepted at the plant «Puhosalmi» (Finland) are the example of it.
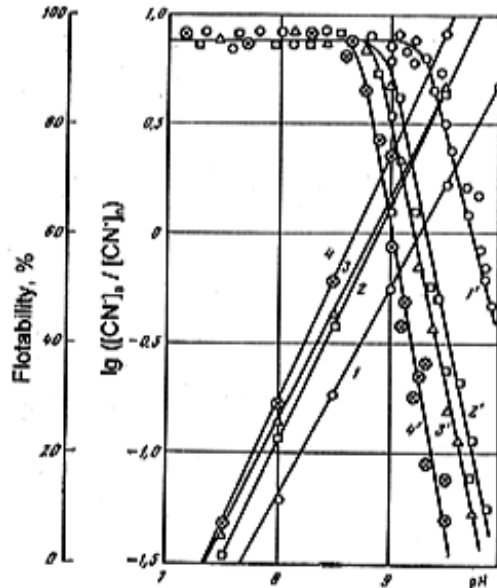
Figure 5. Influence of pH on the ratio of available ($[CN^-]_a$) and critical ($[CN^-]_c$) concentrations of cyanide ions (1 – 4) and floatability (1' – 4') of chalcocite (1, 1'), bornite (2, 2'), covellite (3, 3') and chalcopyrite (4, 4') in the presence of zinc cyanide at $[Cu(CN)_2^-] = 10^{-3}$ mol/l and at $[ButX^-] = 10^{-4}$ mol/l
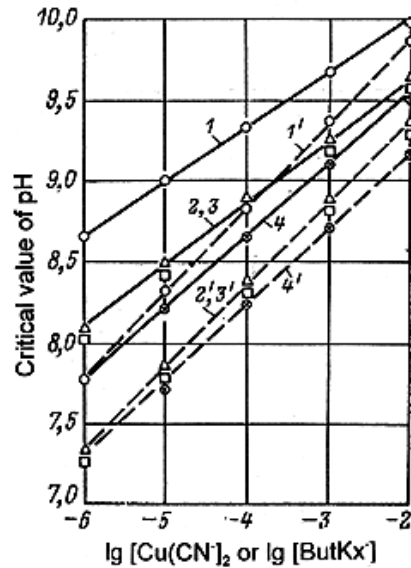

Figure 6. Influence of the concentration of butyl-xanthate (1 – 4) at $[Cu(CN)_2^-]=10^{-3}$ mol/l and the concentration of $Cu(CN)_2^-$ ions (1' – 4') at $[ButX^-]=10^{-4}$ mol/l in the pulp on the critical pH value in flotation of chalcocite (1,1'), bornite (2, 2'), covellite (3, 3') and chalcopyrite (4, 4') in the presence of zinc cyanide

The mixture of cyanide or cyanide flux (200 – 600g/t) with zinc vitriol (700 – 2000g/t) was used at Ural plants in Russia up to 1967 – 1968 years. pH values of the pulp optimal for depression of zinc and iron sulphides in flotation of copper sulphides make up 7.0 – 7.9 (Mitrofanov, 1967; Abramov, 1983). These pH values practically coincide with the critical pH values in flotation of chalcopyrite in the presence of zinc cyanide and usual collector concentrations in the pulp (Figure 6, curves 4, 4').

As the alkali reagent lime is used mainly. In a combination with cyanide it ensures the best results of dressing, the least consumption of cyanide and the most efficient depression of iron sulphides. Grate importance has a place of lime feeding. Charging of lime in a mill and creation of high alkalinity result in violation of flotation selectivity. But if grinding is carried out at low alkalinity (pH 7.4 – 7.7) with cyanide and

zinc vitriol additions and lime is added before flotation, the selectivity of flotation is improved even at alkalinity 100 – 200mg/l of free CaO (Abramov, 1983).

If in grinding of ore a plenty of copper ions is formed in the pulp, the excessively high consumption of cyanide is required for their linkage. Precipitation of these ions partially or completely by charging of xanthate (up to 250g/t) into the mill happens to be more favorable sometimes. Cyanide and other reagents - depressants are fed into the head of flotation. The increase in the concentration of xanthate and $Cu(CN)_2^-$ ions in the pulp due to the increase in critical pH values of copper sulphides flotation (Figures 5 and 6) permits to enlarge consumption of lime and by this way to strengthen the depression of iron sulphides.

The concentration of cyanide in the pulp (in its use as the basic reagent – depressant) will depend on changes in the oxidation degree of ore, size of its grinding, temperature of the pulp, value of pH, composition of water and other factors (Okolovich and Figurkova, 1977). Optimization of cyanide consumption in these conditions can be carried out by the use of the automatic control and regulation system which scheme of principal is shown in Figure 3. Eq. 18 is used in this case as the criteria to the functional control unit of the system.

5. PROCESSING OF POLYMETALLIC ORES

In processing of polymetallic ores cyanide is used in the lead or copper-lead flotation for depression of zinc and iron sulphides, in the bulk and zinc flotation - for activation of zinc sulphides and in the separation of copper-lead concentrates - for depression of copper sulphides.

5.1. Lead or copper-lead flotation

In most cases the lead or lead-copper flotation is carried out in a weak-alkaline (optimal for depression of zinc and iron sulphides by cyanides) medium (pH 7-9) created by sodium carbonate (100-300g/t) usually and less often by lime to exclude some depression of galena flotation.

If the process of Sheridan-Griswold is used, the problem of optimization of lead-copper flotation consists in maintaining in the pulp, firstly, the required CN^- and $Zn(CN)_2^-$ ions concentration values insuring the efficient depression of zinc and iron sulphides but not decreasing the floatability of copper sulphides and, secondly, the required xanthate ions concentration ensuring the most complete recovery of lead and copper sulphides into concentrate.

The latter condition is described by the relationship $[X^-] = f(pH)$ for galena and the first one - by Eq. 49 for chalcopyrite (Abramov, 1978):

$$(29/12)pH - (12/13)lg[Kx^-] + lg\{[Zn(CN)_4^{2-}] / [Cu(CN)_2^-][CN^-]^2\}= lgK \qquad (49)$$

The maximum recovery of copper is attained in the case when the actual lgK value and its value calculated by Eq. 49 are equal (Figure 7).

Reduction in the lgK value due to lower concentrations of cyanide and zinc-containing ions does not cause any increase in the copper recovery, but it disturbs sharply the depression of zinc sulphides and increases their content in the lead-copper concentrate.

Any increase in the value of lgK results in the depression of copper sulphide flotation (Figure 7) and in their losses with tailings. The use of nitrogen instead of air in flotation permits to reduce almost twice the consumption of cyanide and zinc vitriol (Bogdanov *et al.*, 1990).
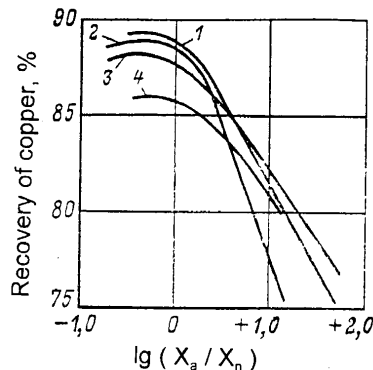

Figure 7. Influence of the ratio of the available and necessary for complete chalcopyrite flotation $[X^-]=[Zn(CN)_4^{2-}]/([Cu(CN)_2^-] [CN^-]^2)$ on the copper recovery into the concentrate of the lead-copper flotation at Belousovskaya plant in various periods of its work (1 - 4)

Conditions of Sheridan-Griswold's process do not affect on the relationship $[X^-] = f(pH)$, if lead sulphides are floating. It is confirmed, for example, by the results obtained at "Zyryanovskaya", "Belousovskaya" and "Sullivan"(Canada) plants (Abramov, 1983). These results indicate also, that an excess of the actual xanthate concentration in slurry over the required one does not result in any appreciable increase in the lead recovery into the concentrate while its excessive sorption on the surface of the bulk lead-copper concentrate causes a dramatic deterioration of conditions for its further separation (Abramov, 1978; 1983).

The scheme of principal for the system of automatic control and regulation of the xanthate and depressors consumption in conditions of Sheridan-Griswold's process is shown in Figure 8.
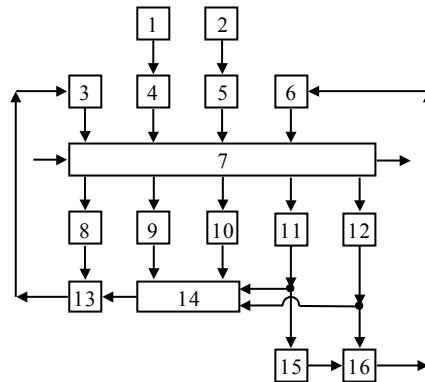

Figure 8. The scheme of principle for the system of automatic control and regulations of the lead or lead-copper flotation in conditions of Sheridan-Griswold's process: 1, 2- task; 3- batcher of cyanide; 4- batcher of zinc vitriol; 5- regulator of the pulp temperature; 6- batcher of xanthate: 7- circuit of selective flotation; 8- transducer of CN^- ions concentration; 9- transducer of zinc concentration; 10- transducer of copper concentration; 11- transducer of pH; 12- transducer of X^- ions concentration; 13- regulator; 14– functional control unit developing the necessary value of CN^- - ions concentration; 15- functional control unit computing $[X^-]=f(pH)$; 16- regulator

The use of automation systems for regulation of xanthate, cyanide and zinc vitriol consumptions in accordance with the derived relationships {Eq. 49 and $[X^-]=f(pH)$ for galena} permits not only to lower the total consumption of reagents essentially but also to improve conditions for the subsequent selective flotation (Abramov, 1983).

5.2. Activation of zinc sulphides in the bulk and zinc flotation.

Increase in efficiency of activation and flotation of zinc sulphides by cyanide additions is used more and more often. The possibility of zinc sulphides activation in this case depends on the quantitative ratio of copper and cyanide ions concentrations in solution (Eqs. 40 and 46).
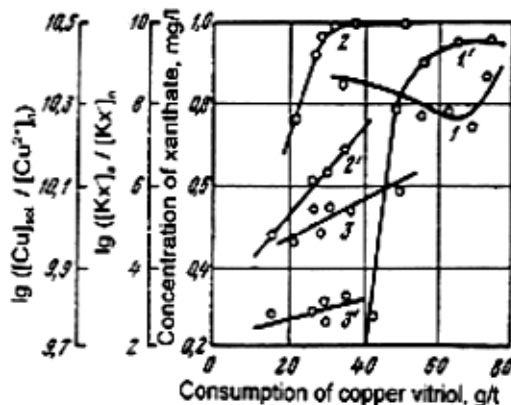

Figure 9. Influence of the copper vitriol consumption on the change in the ratio of dissolved ($[Cu]_{sol.}$) and necessary ($[Cu^{2+}]_r$) for activation of zinc sulphides copper concentrations (1', 1), the value of the xanthate ions concentration (2', 2) and the ratio of available ($[X^-]_a$) and necessary ($[X^-]_r$) xanthate concentration (3', 3) in the pulp in addition of cyanide (1, 2, 3) and in its absence (1', 2', 3')

Okolovich and Figurkova (1977) established that the joint charging of cyanide and copper vitriol increases the recovery of zinc due to reduction in the possibility of copper xanthate formation in the volume of pulp. Cyanide ties copper in a complex playing the role of a buffer, which gives copper off in quantities sufficient for zinc sulphides activation. The ratio of dissolved and necessary for activation of zinc sulphides copper concentrations in addition of 8-12 g/t of cyanide is close to its maximum value. It is reached at the smaller (by 30%) consumption of copper vitriol than without of cyanide additions (Figure 9, curves 1 and 1'). The higher concentration of dissolved copper in the presence of cyanide correlates also with the higher xanthate ions concentration (curves 2 and 2') and values of the ratio of available and necessary xanthate concentrations (curves 3 and 3') due to partial prevention of copper xanthate compounds formation in the volume of pulp in these conditions.
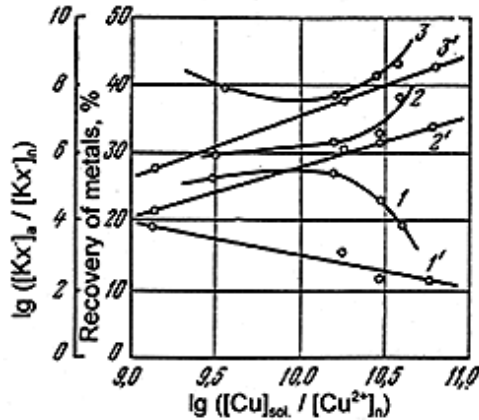

Figure 10. Influence of the ratio of dissolved [Cu]$_{sol.}$) and necessary ([Cu^{2+}]$_r$) for activation of zinc sulphides copper concentrations on the change in the ratio of available ([X$^-$]$_a$) and necessary ([X$^-$]$_r$) xanthate concentrations in the pulp (1', 1), recovery of zinc (2', 2) and lead (3', 3) in the presence of cyanide (1, 2, 3) and in its absence (1', 2', 3')

The use of small additions of cyanide allows running the process of activation and flotation of zinc sulphides at the lower consumption of activator and collector (Figure 10). Decrease in the concentration of xanthate and drawing it near the necessary one both in the absence (curve 1') and in the presence of cyanide (curve 1) in the pulp result in the increase in the recovery of both zinc (2', 2) and lead sulphides (3', 3).

The higher recovery of metals at the cyanide addition (curves 2, 3) despite of large values of ratio of available and necessary xanthate concentrations in the pulp (curves 1 and 1') are caused by sharp reduction in the amount of hydrophobic slimes and their harmful influence on flotation of minerals and frothing in these conditions. It is agree with reduction in the necessary consumption of frother and is confirmed by improvement in the floatability of lead sulphides (curves 3 and 3'). The increase in the lead (by 0.1 - 0.3%) and zinc (by 1.6 - 2.0%) recovery in the intercycle lead-zinc flotation at Almalikskaya plant (Uzbekistan) at cyanide addition was accompanied also by increase in the assay of lead (by 0.5 - 1.06%) and zinc (by 0.7 - 2.0%) in the bulk concentrate (Abramov and Shahmatova, 1979).

5.3. Cyanide separation of copper-lead concentrates

Stability of the depression of copper sulphides by cyanides depends appreciably on the mineral solubility. For example, chalcopyrite does not dissolve practically in cyanides and after dissolution of xanthate compounds on its surface the concentration of cyanide in the pulp changes insignificantly providing the stable depression of this mineral. Oxide minerals and secondary sulphides of copper (covellite and chalcocite), on the contrary, are easily soluble in cyanides. Therefore, the concentration of free CN$^-$ ions in the pulp will be decreased all the time and the concentration of Cu(CN)$_2^-$ ions - to grow causing increase in the concentration of copper ions in conformity with the equation of convertible reaction (Eq. 43). As a result of it the dissolution of xanthate compounds on the mineral surface and depressing action of cyanide can be stopped. It explains considerably worse stability of secondary copper sulphides depression as compared with chalcopyrite and unsatisfactory results of their separation from lead sulphides by cyanide technology. The defect of cyanide technology consists also in the high consumption of cyanide, as a result of which the significant quantity of gold (up to 4 - 8%) is dissolved and lost with tailings of separation of copper - lead concentrates. Besides that wastewaters of this operation are contaminated with cyanides (Abramov, 1983).

A possibility for cutting down of cyanide consumption follows from the analysis of physico - chemical models (Eqs. 15–18) for copper sulphides.

For example, taking into account the numerical values of the constants, Eq. 15 for chalcocite can be represented as:

$$lg[CN^-] = 0.42 + (1/2)lg[Cu(CN)_2^-] + (2/6)lg[ButX^-] + (1/12)pH \qquad (50)$$

Such shape of Eq. 15 shows clearly that the concentration of cyanide $[CN^-]$ required and its consumption will be the smaller the less pH value and the concentration of $Cu(CN)_2^-$ and $ButX^-$ ions in the pulp. Hence, the cyanide consumption can be cut down, if to carry out in correspondence with the relationship (50) at plants:

➢ diminution of the X^- ions concentration in the pulp to its minimum required for the lead sulphide flotation by feeding of the activated carbon or ion-exchange resin. It can be also realized by preliminary desorption of collector from the surface of copper minerals at small cyanide or sodium sulphide concentrations in the presence of xanthate absorbent;

➢ diminution of the $Cu(CN)_2^-$ ions concentration by using of absorbent, passivation of the secondary copper sulphides surface by zinc-cyanide compounds or creation of conditions for the least their surface oxidation by addition of reducing reagents which do not exert influence on the lead sulphides floatability;

➢ diminution of the pH value to 10.0-10.5, for example, by additional sodium carbonate feeding to create the buffer system.

Practical realization of these ways for cutting down of cyanide consumption at plants is possible through the use of automatic control systems for regulation of concentrations of X^-, H^+, CN^-, $Cu(CN)_2^-$ ions in the pulp in correspondence with Eqs. 15-18.
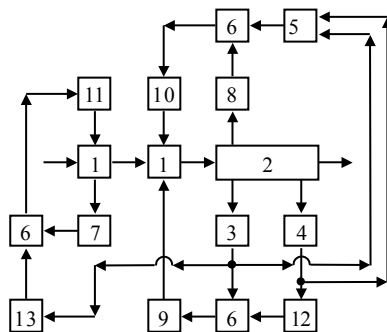

Figure 11. The possible flowsheet of principal for the system of automatic control and regulation of the process of cyanide separation of lead - copper concentrates: 1- tank for mixing: 2- flotation; 3- transducer of the X^- ions concentration; 4- transducer of pH; 5- functional control unit computing $[Cu(CN)_2^-]/[CN]_2^-=f(pH, [X]^-)$; 6- regulator; 7- transducer of the S^{2-} - ions concentration; 8- transducer of the $[Cu(CN)_2^- / [CN^-]^2$ ratio; 9- batcher of the activated carbon; 10- batcher of cyanide; 11- batcher of sodium sulphide; 12- functional control unit computing $[X^-] = f(pH)$; 13- functional control unit computing $[S^{2-}]_c=f[X]$

In the simplest case, when copper sulphides in the lead-copper concentrate are represented only by chalcopyrite, the efficient monitoring and control of cyanide separation of concentrates at plants can be ensured by the automatic control system which scheme of principal is shown in Figure 3b. Eq. 18 for chalcopyrite is employed in this case as a criterion for the functional control unit (10).

Such automatic control system can be employed as well when other sulphides or their mixture represents copper in the concentrate. In this case Eq. 15 for chalcocite requiring the largest cyanide concentration for its depression is employed in the functional control unit 10. But it is necessary to take into account that the presence of secondary copper sulphides in the concentrate will require large cyanide consumption. More expedient automatic control system scheme for such cases is shown in Figure 3c.

This system version differs from the previous one (Figure 3b) by the presence of the additional automatic system. It permits to realize the preliminary desorption of collector from the copper sulphides surface with small cyanide concentration. As the criterion for regulation system of cyanide consumption Eq. 15 for chalcocite is employed. Diminution of $[X^-]$ in the pulp to the minimal-required one permits to decrease the cyanide consumption in desorption and lead-copper separation circuits. Cyanide consumption can be decreased much more, if the signal of the regulator 5 is used for regulation not only of the consumption of adsorbent for the excessive $[X^-]$ but also of consumption of the ionic-exchange resin able to absorb copper-cyanide complexes.

Maximal decrease in the cyanide consumption can be reached, if the automatic control system shown in Figure 11 will be realized.

This system in comparison with the previous one (Figure 11b) has the additional autonomous control system for regulation of consumption of sodium sulphide charged into the vat (1). As the criterion for the functional control unit (9) the equation $[S^{2-}]=f(pH)$ for galena is used (Abramov, 1978; 1983):

$$lg[S^{2-}] - 2lg[X^-] = lgK \qquad (51)$$

The presence of S^{2-} ions in the pulp will hamper interaction of secondary copper sulphides and sulphidized oxide copper minerals with cyanide and promote destruction of copper xanthate on their surface.

5.4. Zinc-cyanide separation of copper-lead concentrates

The most efficient method for separation of lead-copper concentrates containing bornite, chalcocite and chalcopyrite was offered by Eropkin (1999). The method is based on depression of copper sulphides in sodium carbonate medium with the mixture of cyanide and zinc sulphate taken in the 1:1 ratio necessary for formation of zinc-cyanide salt $Na_2[Zn(CN)_4]$.
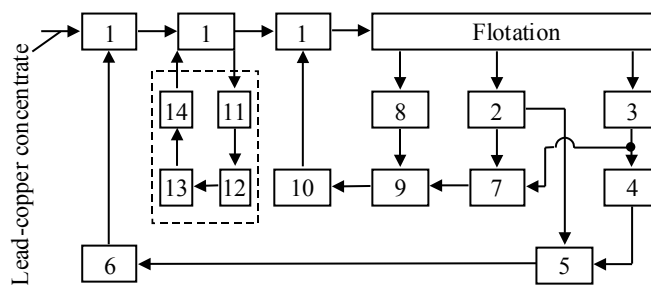

Figure 12. Flowsheet of principle for the system of automatic control and regulation of the zinc - cyanide separation of the lead - copper concentrate: 1- conditioning cells; 2- transducer of the X^- ions concentration; 3- transducer of pH; 4- functional control unit computing $[X^-]=f(pH)$; 5- regulator; 6- batcher of the activated carbon; 7- functional control unit computing $\{[Zn(CN)_4^{2-}]/([Cu(CN)_2^-] [CN^-]^2)\}=f([X^-], pH)$; 8- transducer of the ratio $[Zn(CN)_4^{2-}]/([Cu(CN)_2^-] [CN^-]^2$; 9- regulator; 10- batcher of sodium cyanide; 11- transducer of concentrations; 12- high-resistance converter; 13- regulator; 14- batcher of zinc vitriol

A possible scheme of principal for automatic control system of Eropkin's process regulation is shown in Figure 12. As the criterion for the functional control unit 11 Eq. 52 for chalcocite is employed:

$$(11/6)pH - (2/3)lg[X^-] + lg\{[Zn(CN)_4^{2-}]/[Cu(CN)_2^-][CN^-]^2\}= lgK \qquad (52)$$

In turn, the equation $[X^-]=f(pH)$ for galena is used as the criterion for the functional control unit 8 to secure the possible complete recovery of lead sulphides in separation of lead-copper concentrates. The efficiency of such automatic control and regulation has been proved in dressing of lead-copper ores of Jezkazgan deposit in Kazakhstan (Abramov, 1983).

6. REGENERATION AND REUSING OF CYANIDE-CONTAINING SOLUTIONS

The further reduction in cyanide consumption can be reached through the regeneration and reusing of cyanide-containing solutions. It can be carried out with the active carbon or ion exchange resins and would be accompanied with an additional recovery of dissolved gold, silver and copper from the liquid phase of the pulp (Abramov, 1983).

The active carbon is used at "Leninogorskaya" plant. Its suspension prepared before is feeded to the vet-mixer (with carbon consumption 1.3-1.5kg/m³ of the cyanide-containing overflow of the copper thickener) and undergo to the separate thickener for carbon sedimentation during 3-4 hours. The sediment is filtered and made for copper melting works, the overflow can be reused.

The technology of ion exchange for cleaning of cyanide-containing waters is realized at "Zyryanovskaya" plant. The best results were received when resin AB-17-4 was utilized. It had the largest capacity with respect to copper compounds and negligible wear. For regeneration of the resin the scheme of selective recovery of metals from its surface, continuous electrolytic cleaning and reusing of regenerated solution was used.

The both regeneration technologies ensure the high recovery of gold from cyanide-containing solutions (up to 87%) and reusing of these solutions in technological processes after their regeneration (Abramov, 1983).

7. CONCLUSIONS

Physico-chemical modeling of flotation phenomena and processes allows explaining both activation and depression of sulphide minerals flotation in the presence of cyanide and determining their regularities.

Physico-chemical models derived for various cyanide processes in flotation can be used in automatic control systems at the mineral processing plants for optimization of cyanide processes of sulphide minerals selective flotation, improvement of technological indices, cutting down of cyanide consumption down and conditioning of recycle waters to prevent environment pollution.

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