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# Comprehensive study of the distribution of metals during the smelting of copper-containing raw materials in the Vanyukov furnace at the Balkhash copper smelter

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## ABSTRACT

This paper analyzes the distribution of Cu, Pb, Au, and Ag between matte and slag during the melting of a multicomponent copper-containing charge onto matte in a Vanyukov furnace in the Balkhash Copper Smelter of Kazakhmys Corporation LLP. Based on the analysis of a large array of production data on the composition of matte and slag, general trends in the distribution of metals between matte and slag have been identified. The results of studying the effect of basicity ($j_{bas.}$) and slag composition on the metal distribution coefficient between matte and slag are presented. The main focus is on determining the distribution coefficient of Cu, Pb, As, Au, Ag between matte and slag, depending on the composition of the slag. It is proved that it is more expedient to use models based on the composition of the slag rather than on the basicity coefficient to predict the distribution coefficient of the studied elements. Based on the results obtained, the possibility of improving the existing technology is demonstrated by regulating and establishing the optimal slag composition, which ensures an equilibrium distribution of metals between matte and slag. It is shown that when melting a multicomponent charge onto a matte in a VP furnace, it is necessary to maintain the $SiO_2$ content in the slag at the level of 23 wt.%, the $FeO/SiO_2$ ratio = 2.3–2.5 and the calcium oxide content of 8–10 wt.%. At the same time, the best indicators for the distribution of metals between the melting products are achieved, close to towards equilibrium.

**Keywords:** metals, matte, slag, intermediates, recycled materials, partition coefficient, loss of metals with slag.

## INTRODUCTION

One of the key, if not the most important, tasks for enterprises engaged in non-ferrous metallurgy is to solve the issue of processing accumulated and generated slag waste from autogenous smelters. These wastes occupy vast areas and have a serious negative impact on the environment and human living conditions [1–3]. In the modern world, approximately 2.2–3 tons of slag containing copper are formed during the production of each ton of copper. It is estimated that annual copper losses in slags reach about 4 million tons in the USA and 2 million tons in Japan [4].

Losses of non-ferrous metals with slags have a strong impact on the economy of their production, negatively affect environmental protection, exacerbating the environmental problems of the enterprise as a whole. This has become a global problem that every company is trying to solve using locally available resources and technical means [5, 6].

The issue of copper losses with slag has been studied in sufficient detail in relation to modern autogenous copper production processes. One of the promising approaches to the processing of slag waste is the use of modern bubbling technologies such as the Vanyukov process and Isasmelt. Despite the innovation and originality of the proposed solutions, none of the existing methods fully meets the requirements for both the degree of extraction of non-ferrous metals from slags and the variety of valuable components and elements extracted. No studies have studied in detail the distribution of gold and silver between the products of autogenous smelting. Moreover, each of these methods has a complex technical design and requires significant material and energy costs.

Losses of copper with slag during autogenous smelting depend on a number of factors, ranging from objective ones, which are determined by the composition of the input materials, the physicochemical structure and composition of the smelting products, and subjective factors, depending on the process control [5].

In VF, total copper losses in slag are determined by the sum of electrochemical (chemical and physical) and mechanical losses [7, 8]. At the same time, electrochemical losses amount to 65–80%, and mechanical losses amount to 20–35% of the total copper content in the slag [7]. However, the current state of VP operation at the BCS for melting multicomponent copper charge onto matte shows large losses of copper with slag, which is due to the redistribution of the quantitative ratios of dissolved and mechanical losses of copper [9, 10].

Systematic studies of the microstructure of industrial slags from a VF siphon, an electric sump and converter slags with a study of the distribution of metals between melting products, in relation to the conditions of the BCS, were carried out in [11]. The authors showed that for the richest of the studied converter slags and slags from the siphon of the Vanyukov furnace, the proportion of copper in the matte slurry is noticeably higher than the proportion of copper in the dissolved form and can reach ≈80–85% of the total copper content in the slags. The measures envisaged at the BCS to reduce the loss of metals with slag using additional equipment (electrically heated settling tanks) and by flotation do not provide the desired effect.

In modern studies [12], the problem of mechanical losses of copper with slag during autogenous smelting is also noted. However, they do not consider the complex behavior of a wide range of elements, including precious metals, in relation to the specifics of the BCS raw materials.

The development of mathematical models for predicting the distribution of metals between VP products is an urgent area of research in metallurgy [13]. In particular, in [14], the authors propose using thermodynamic models to optimize the VF process, taking into account the specific features of the BCS process.

In modern literature, more and more attention is being paid to the integration of mathematical models into process control systems [15]. This makes it possible to increase production efficiency and reduce costs.

Despite the widespread coverage in the scientific literature of the results of studies on copper losses with slag [16, 17], as well as works devoted to the creation of thermodynamic models predicting copper losses with slag [4], information about the solubility and behavior of gold and silver during charge melting on matte in VF, especially in relation to complex raw materials The resources used at the BCS are extremely limited.

The purpose of this work is to study the effect of slag composition on the distribution of Cu, Pb, As, Au, Ag between matte and slag during melting of multicomponent copper–containing raw materials in VF under BCS conditions and to build mathematical models predicting the distribution of metals during melting.

The scientific novelty of the work consists in a comprehensive study of the distribution of Cu, Pb, As, Au, Ag between matte and slag under melting conditions of multicomponent copper-containing raw materials in the Vanyukov furnace at the BCS. In contrast to existing studies focusing mainly on copper, for the first time a detailed analysis of the behavior of a wide range of valuable and harmful elements, including precious metals, has been carried out, taking into account the specifics of the raw materials and technological parameters of the BCS.

Mathematical models have been developed that predict the distribution of metals (Cu, Pb, As, Au, Ag) between matte and slag, taking into account the influence of slag composition (iron oxides, silica, lime, and other components) for melting conditions in VF. The proposed models make it possible not only to predict metal losses, but also to optimize technological parameters to increase the extraction of valuable components.

The integration of the developed mathematical models into the process control system at the BCS will make it possible to switch from empirical control of the melting process to scientifically sound, promptly adjusting the parameters depending on changes in the composition of raw materials and the quality requirements of the matte, which will ensure the stability of the Vanyukov furnace and minimize deviations from optimal modes.

Ultimately, the results of the study will make it possible to create a tool for making informed decisions in the field of managing the smelting process, which will lead to increased economic efficiency and environmental safety of copper smelting. Further development of modeling may include consideration of hydrodynamic factors and the development of three-dimensional models describing the distribution of temperature and concentrations of components in the volume of the Vanyukov furnace.

## Source materials and research methods

The work uses the results of industrial experiments on the processing of multicomponent copper-containing charge into matte in VF at the BCS.

At the BCS, the Vanyukov furnace processes a wide range of copper-containing sulfide materials with a variety of chemical compositions. Melting is carried out on matte with a copper content of 50–55%. The average composition of the melting charge contains (wt.%): 16.9 Cu; 1.19 Pb; 2.0 Zn; 26.6 Fe; 29.3 S; 14.4 $SiO_2$; 2.6 $Al_2O_3$; and others.

The composition of the charge includes concentrates from KazMinerals LLP (KM), own concentrates (KSS), concentrates from outside (Imported), recycled dust (VF dust) and fluxes. To increase the sulfur content, up to 8% pyrite concentrate is added to the charge.

Copper sulfide concentrates of KazMinerals LLP (KM) contain 19–24% copper and 26.2–32.5% sulfur. The gold content in them varies from 0.93 to 6.75 g/t, with the exception of the concentrate of the Bozymchak deposit, where, with a sulfur content of 22.7%, the gold content reaches 30 g/t. The share of KMM in the charge is 27.2%, and in terms of copper content it is 36.8%.

The share of own concentrates (KSS) with an average copper content of 31.2% and sulfur of 28.1% is 33.3%. Own concentrates are a mixture consisting of: Zhezkazgan concentrates containing on average ~32% Cu and 16.0% S; ore concentrates from own processing plants with a content of 18.1–24% Cu, 22.1–28% S; pyrite concentrates from Karagaila with a content of up to 10.5% Si and 30–39% S. The share of KSS in the charge is up to 8%.

In the charge structure, the bulk of the purchased concentrates (Imported) accounts for the concentrates of the Aktobe Copper Company, whose share in the charge is 22.8% of the total weight. These concentrates are characterized by an average copper content of about 19% and sulfur content of 35% by weight. In terms of their characteristics, they are similar to KMM concentrates and play a key role in the formation of the charge composition.

Together with imported concentrates, Zhaisan concentrates and Trafigura gold-bearing concentrates are introduced into the charge, which do not contain copper, but are characterized by a high content of sulfur (30%) and gold (23.7 g/t). A significant amount of arsenic is added with these concentrates (approximately 7%). Despite the fact that the proportion of these materials in the charge is small – only 2.4%, up to 35% of the total arsenic present in the charge enters the smelting process.

The share of concentrates (COF) obtained as a result of flotation during the processing of intermediates of our own production (slag from melting furnaces and slag from converter processing) in the charge structure is insignificant and amounts to 0.2%. These concentrates are characterized by low copper and sulfur content (8 and 12%, respectively) and high magnetite content.

Return dusts (VF dust) account for about 3% of the mass of the charge. There is a high content of lead (18%) and arsenic in them. The involvement of return dust for processing leads to the accumulation of Pb, As in the general technological scheme of copper production.

The practice of long-term operation of VP technology shows that the content of the main components of slag varies in the range (%): 22–23 $SiO_2$; 42–44 FeO; ~2 ZnO; 1–3 CaO. The copper content in matte varies from 50 to 55% [14].

For statistical analysis, the results of factory analyses of replaceable samples of matte and slag compositions were taken, obtained with the following daily performance indicators of VP:

1. 1.145 tons of copper matte with a copper content of 52.4%, which was sent for further processing by conversion.
2. 2073 tons of slag containing 1.57% copper, 0.67% lead and ~2.5% zinc.
3. The temperature in the furnace above the slag melt was maintained at 1573 K.

The selected parameters ensured stable operation of the furnace. The analyzed statistical set of processed paired samples of matte and slag contained 125 values per component. This made it possible to carry out a reliable assessment of the distribution of elements between matte and slag and to identify significant dependencies of their distribution coefficients on the composition and basicity of the slag.

Control measurements for the determination of non-ferrous metals and minor elements with a content of less than 0.1% in the melting products were carried out using an Optima 2000 DV spectrometer (Perkin Elmer Inc., USA); a D8 ADVANCE X-ray diffractometer and a Venus 200 PANalytical B.V. X-ray fluorescence spectrometer with wave dispersion (PANalytycal B.V., the Netherlands). Such an integrated approach to determining the elemental composition of the studied samples ensured high accuracy and reliability of the results obtained.

A sample of the compositions of industrial matte and slag from the total array is shown in Table 1. Linear and multiple regression methods are widely used to predict the distribution of copper (Cu), gold (Au), and silver (Ag) between slag and matte based on the composition of slag (FeO, $SiO_2$, ZnO, and CaO). These methods make it possible to establish and quantify the relationship between the composition of slag (independent variables) and the distribution of metals (dependent variables).

Numerous studies of the influence of the conditions of oxidative melting of copper raw materials on matte, conducted earlier [7, 8, 11, 12], It was found that the main parameters affecting the distribution of copper, precious metals, and impurity metals with a similar composition of the initial copper materials is the copper content in matte, which increases under more oxidizing conditions. melting, which leads to an increase in copper losses in the oxide form. In addition, there is an increase in the copper content in the matte droplets, as a result of which, with the same proportion of matte droplets in the slag, it leads to an increase in mechanical losses. The increase in oxide losses is also influenced by an increase in the basicity of the slag due to an increase in the ratio of iron oxide to silica. These parameters, as well as the influence of a modifier such as CaO, have a major impact on copper losses with slag. In this regard, they were chosen for the development of regression equations.

The fundamental principles of regression analysis were based on linear, multiple regression and the least squares method. Based on a linear relationship, we sought to find the "best" direct line describing the dependence of the distribution coefficient of copper, gold and silver on each individual component of the slag.

Multiple regression extends linear regression to account for the influence of several independent variables (FeO, $SiO_2$, ZnO, CaO) on a dependent variable (metal distribution).

The least squares method was used as the main method for estimating model parameters. The goal is to minimize the sum of the squares of the differences between the actual values of the metal distribution and the values predicted by the model.

In the regression analysis, the following assumptions were used for the correctness of the results:

- The relationship between the independent and the dependent variable should be linear.
- The residuals (differences between the actual and predicted values) should be independent of each other.
- The variance of the residuals should be constant for all values of the independent variables.
- The leftovers should be normally distributed.
- For multiple regression, the independent variables (FeO, $SiO_2$, ZnO, CaO) should not be strongly correlated with each other. The high correlation makes it difficult to determine the individual contribution of each variable to the prediction of metal distribution.

The correlation coefficient r was used as a method for evaluating and interpreting the results, which shows how much of the variance of the dependent variable (metal distribution) is explained by the model.

The p-values showed the statistical significance of the regression coefficients. The low established p-values ($p < 0.05$) for the prediction equations of the distribution coefficient of copper, gold and silver depending on the composition of the slag indicate that the corresponding coefficient is statistically significant, that is, it is not zero.

The application of regression analysis to industrial data allows:

1. To evaluate the effect of various slag components (FeO, $SiO_2$, ZnO, CaO) on the extraction of Cu, Au and Ag into matte or slag.
2. To identify optimal slag compositions that

**Table 1.** Chemical composition of mattes and slags obtained from matte smelting in the VF at BCS

| Serial No. | Matte composition, wt.%. | | | | | | | Slag composition, wt.%. | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | [Cu] | [Pb] | [Zn] | [Fe] | [S] | [Au]* | [Ag]* | Cu | Pb | ZnO | $SiO_2$ | FeO | CaO | Au* | Ag* |
| 1 | 59.71 | 0.73 | 0.12 | 15.81 | 22.30 | 14.59 | 214.22 | 1.73 | 0.78 | 2.44 | 22.77 | 56.37 | 1.97 | 0.31 | 7.21 |
| 2 | 61.42 | 0.90 | 0.12 | 14.09 | 21.05 | 14.75 | 214.72 | 1.93 | 0.83 | 2.61 | 23.24 | 57.11 | 2.04 | 0.37 | 7.31 |
| 3 | 65.57 | 1.06 | 0.10 | 11.21 | 20.44 | 15.21 | 215.13 | 2.15 | 0.92 | 2.57 | 22.30 | 57.01 | 1.91 | 0.35 | 8.54 |
| 4 | 58.91 | 1.08 | 0.10 | 16.17 | 22.04 | 14.37 | 214.17 | 1.68 | 0.78 | 2.40 | 22.56 | 56.26 | 1.78 | 0.29 | 7.76 |
| 5 | 57.28 | 1.09 | 0.17 | 16.97 | 22.18 | 14.22 | 213.54 | 1.58 | 0.73 | 2.32 | 23.59 | 56.16 | 1.79 | 0.28 | 6.60 |
| 6 | 61.74 | 1.26 | 0.10 | 13.42 | 21.24 | 14.88 | 214.21 | 1.98 | 0.87 | 2.67 | 23.38 | 57.16 | 1.76 | 0.32 | 8.11 |
| 7 | 54.71 | 1.37 | 0.20 | 19.04 | 22.88 | 13.95 | 213.54 | 1.32 | 0.46 | 2.32 | 23.26 | 55.36 | 1.85 | 0.24 | 7.54 |
| 8 | 49.72 | 1.13 | 0.17 | 22.94 | 23.77 | 13.55 | 213.05 | 1.12 | 0.42 | 2.24 | 24.75 | 55.12 | 1.96 | 0.24 | 6.53 |
| 9 | 50.53 | 1.11 | 0.18 | 22.29 | 23.73 | 13.68 | 213.11 | 1.20 | 0.56 | 2.34 | 24.22 | 55.05 | 1.84 | 0.25 | 7.43 |
| 10 | 52.10 | 1.43 | 0.19 | 20.31 | 23.45 | 13.88 | 213.16 | 1.24 | 0.52 | 2.38 | 23.66 | 55.11 | 1.87 | 0.27 | 7.23 |
| 11 | 57.17 | 1.12 | 0.15 | 17.23 | 22.31 | 14.28 | 213.80 | 1.57 | 0.70 | 2.54 | 23.37 | 56.07 | 1.88 | 0.29 | 7.66 |
| 12 | 50.78 | 1.15 | 0.24 | 22.56 | 23.59 | 13.75 | 213.10 | 1.17 | 0.57 | 2.20 | 23.68 | 55.68 | 1.86 | 0.25 | 6.22 |
| 13 | 57.81 | 1.28 | 0.10 | 16.87 | 22.16 | 14.33 | 214.00 | 1.62 | 0.75 | 2.78 | 22.96 | 55.93 | 2.11 | 0.28 | 7.06 |
| 14 | 55.97 | 1.33 | 0.14 | 18.52 | 22.94 | 13.87 | 213.34 | 1.42 | 0.42 | 2.60 | 22.59 | 56.82 | 2.16 | 0.27 | 7.50 |
| 15 | 54.12 | 1.43 | 0.12 | 19.81 | 23.33 | 13.75 | 213.38 | 1.28 | 0.60 | 2.43 | 22.38 | 56.49 | 1.96 | 0.25 | 6.94 |
| 16 | 54.55 | 1.53 | 0.21 | 19.43 | 23.16 | 13.79 | 213.33 | 1.39 | 0.56 | 2.39 | 23.08 | 54.78 | 1.79 | 0.27 | 7.33 |
| 17 | 59.43 | 1.09 | 0.14 | 16.38 | 21.46 | 14.67 | 214.24 | 1.74 | 0.70 | 2.68 | 22.26 | 57.48 | 2.03 | 0.31 | 8.69 |
| 18 | 52.72 | 1.34 | 0.28 | 20.13 | 23.18 | 13.89 | 213.34 | 1.20 | 0.58 | 2.23 | 23.48 | 56.89 | 1.73 | 0.25 | 6.25 |
| 19 | 55.90 | 1.27 | 0.13 | 17.83 | 22.45 | 13.99 | 213.57 | 1.56 | 0.66 | 2.61 | 23.48 | 55.44 | 2.51 | 0.29 | 7.58 |
| 20 | 62.87 | 1.11 | 0.10 | 12.93 | 20.09 | 15.01 | 214.87 | 2.06 | 0.81 | 2.74 | 23.14 | 55.74 | 3.42 | 0.36 | 8.10 |
| 21 | 64.99 | 1.06 | 0.10 | 12.08 | 19.58 | 15.11 | 215.04 | 2.20 | 0.92 | 2.78 | 23.41 | 56.37 | 3.42 | 0.36 | 8.22 |
| 22 | 57.05 | 1.18 | 0.15 | 17.43 | 22.25 | 14.20 | 213.19 | 1.49 | 0.69 | 2.51 | 23.22 | 56.11 | 2.08 | 0.28 | 7.09 |

**Note:** * content, g/t.

maximize the extraction of valuable metals.

3. Predict metal losses in the slag when the slag composition or technological parameters of the process change.
4. Optimize the technological parameters of smelting to increase the extraction of valuable metals and reduce losses.

## The results and their discussion

When melting onto matte in a multicomponent charge, the distribution of metals between matte and slag is complicated due to the influence of various factors. The calculated values for the distribution of metals between matte and slag obtained during melting of the existing multicomponent charge shown in Figure 1 confirm this position.

The difficulty of predicting the distribution of metals is related to the nonlinear nature of the interaction of the charge components, the variable composition of the raw materials used and fluctuations in the technological parameters of melting. Deviations of the actual indicators of metal extraction in matte from the theoretically calculated ones are observed. This leads to a decrease in the efficiency of the process and an increase in the loss of valuable components with slag.

To increase the accuracy of forecasting and optimize the melting process, an integrated approach is needed, including a more detailed study of the physico-chemical properties of the charge components, the development of mathematical models that take into account the interaction of various factors, as well as the introduction of automated process control systems.

Under the conditions of melting a multicomponent charge of complex composition in PV, the distribution of non-ferrous and related metals is influenced by the viscosity, solubility of metals in slag, melting point of slag, and partial pressure of oxygen. The composition of the slag and its basicity have the greatest effect on the distribution of metals between slag and matte [18, 19].

The BCS slag formed during melting in VF is characterized by a complex chemical

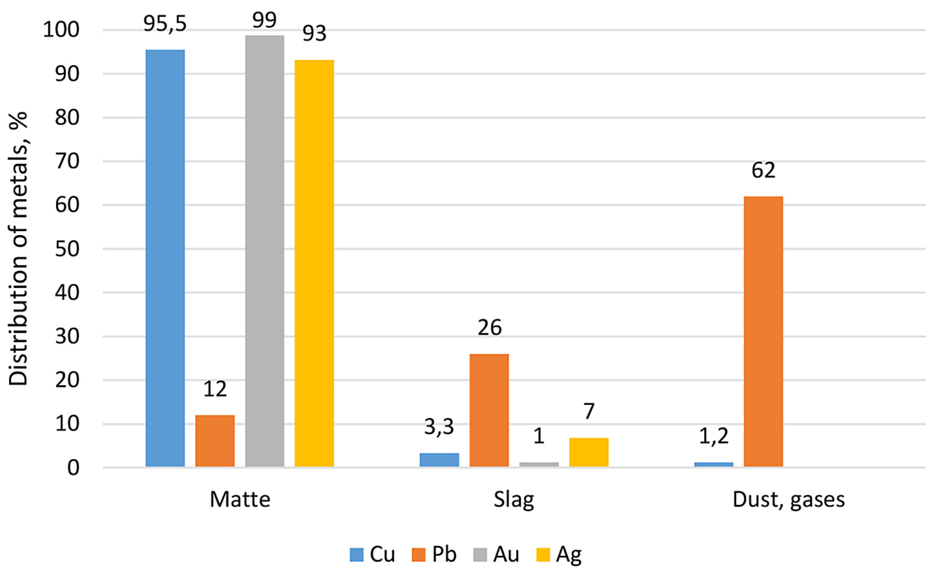


**Figure 1.** Distribution of metals between VP melting products

composition. In addition to $SiO_2$ and FeO (up to 80% in total), they contain CaO, MgO and $Al_2O_3$, which have a significant effect on the physico-chemical properties of the slag, for example, on viscosity. It was found in [12] that the dynamic viscosity of the $SiO_2$ – FeO – CaO – MgO – $Al_2O_3$ slag system at a given temperature increases with an increase in the content of $SiO_2$ and $Al_2O_3$ and decreases with an increase in the content of CaO and FeO. The viscosity of the slag is the most important parameter and determines the completeness of the separation of slag from matte, the loss of non-ferrous metals with slag, and the stability of the furnace process [7]. In this case, the equilibrium distribution of metals between matte and slag and their final solubility in slag is determined by the oxidizing ability of the slag.

To determine the oxidizing ability of slag, the basicity coefficient ($J_{bas}$) is often used as a suitable indicator, which is defined as the ratio of the sum of the content of basic oxides to the sum of acid oxides [19]:

$$J_{bas.} = (\%FeO + \%CaO + \%MgO) / (\%SiO_2 + \%Al_2O_3) \quad (1)$$

As can be seen from expression (1), the basicity coefficient of the slag includes all the main components, allowing for an assessment of its influence on the distribution of metals between the matte and the slag.

The distribution coefficients of copper, lead, and other elements between the matte and slag were determined based on the expression:

$$L_{Me} = [Me] / (Me) \quad (2)$$

where: $[Me]$ – metal content in matte, wt.%;
$(Me)$ – metal content in slag, wt.%.

The distribution coefficients of Cu, Au, and Ag between the matte and slag were calculated based on a large dataset of industrial data on the compositions of mattes and slags.

The selection of additional related components is dictated by the fact that almost all intermediates and materials processed in the Vanyukov furnace are characterized by a significant content of gold and silver. Their behavior during the melting process is closely related to the distribution of non-ferrous metals in various phases.

Considering the close correlation of noble metals with copper and lead, it can be stated that the basicity of the slag has a strong impact on their distribution between the slag and the matte. Based on the analysis of variance, equations were obtained that describe the dependence of the distribution coefficient ($L_{Me}$) on the basicity of the slag ($J_{bas.}$):

$$L_{Cu} = 115.17 - 31.09 \times J_{bas.},\ r = 0.49 \quad (3)$$

$$L_{Pb} = 9.18 - 2.91 \times J_{bas.},\ r = 0.4 \quad (4)$$

$$L_{Au} = 122.37 - 29.02 \times J_{bas.},\ r = 0.45 \quad (5)$$

$$L_{Ag} = 68.01 - 15.51 \times J_{осн.},\ r = 0.53 \quad (6)$$

The insignificant values of the pairwise correlation coefficients in Equations 3–6 indicate a weak relationship between the studied parameters. This indicates the low efficiency of these equations for predicting the distribution coefficients of the elements under consideration.

It is likely that the equations describing the dependence of the distribution coefficients of metals on the composition of the slag possess the highest accuracy. Statistical processing of industrial data revealed a number of characteristic dependences of the calculated values of the Cu, Au, and Ag distribution coefficients on the slag composition. Due to the low correlation of the distribution coefficient of lead with the sought parameters (r = 0.4), the behavior of lead will not be considered in further analysis and discussion.

The multiple correlation equations predicting the distribution coefficients of Cu, Au, and Ag from the composition of the slag have the following form:

$$L_{Cu} = 155.74 - 16.38 \times ZnO + 0.17 \times SiO_2 - 1.81 \times FeO - 1.31 \times CaO,\ r = 0.82 \quad (7)$$

$$L_{Au} = 185.42 - 13.29 \times ZnO - 0.14 \times SiO_2 - 2.13 \times FeO - 2.99 \times CaO,\ r = 0.79 \quad (8)$$

$$L_{Ag} = -5.01 - 10.23 \times ZnO - 1.18 \times SiO_2 - 0.55 \times FeO - 0.38 \times CaO,\ r = 0.74 \quad (9)$$

The values of the coefficients in Equations 7–9 are determined experimentally. However, their polarity and magnitude ratio may indicate underlying physical and chemical processes.

The negative coefficients for ZnO, FeO, and CaO in the equations for $L_{Cu}$, $L_{Au}$, and $L_{Ag}$ indicate that an increase in the content of these oxides in the slag reduces the metal distribution coefficient, that is, increases the transition of metal to matte. It is assumed that ZnO can interact with Cu and Au to form complexes or solid solutions that are more stable in matte, thereby retaining these metals in matte and reducing their transition to slag. This is due to the acid-base properties of ZnO and its ability to form covalent bonds with sulfides (in matte).

FeO, as a strong oxide, promotes the formation of more stable oxide compounds with Cu, Au, and Ag in the slag. Its effect on matte may be more complex, possibly by changing the activity of sulfur and, consequently, affecting the solubility of precious metals. Higher concentrations of FeO can shift the equilibrium towards the matte. FeO can also affect the viscosity of the slag, which in turn affects the kinetics of the processes.

By interacting with other oxides in the slag, CaO changes its general physico-chemical properties (viscosity, basicity). The mechanism of influence of CaO may be indirect, affecting the activity of other slag components and, consequently, the distribution of metals.

A positive coefficient for $SiO_2$ (although small) in the equation for $L_{Cu}$ indicates an increase in the $SiO_2$ content and promotes the transition of copper to slag. This is due to the fact that $SiO_2$, being a strong acidic oxide, can interact with basic oxides, changing the structure of the slag and affecting the activity of copper. An increase in $SiO_2$ leads to a decrease in the viscosity of the slag, which facilitates the transition of copper into slag.

High values of the correlation coefficients r (about 0.8) indicate a strong relationship between the composition of the slag and the distribution coefficients, but do not mean a causal relationship. It should be borne in mind that these are empirical correlations, and there may be other factors not included in the equations. For example, it is known that copper losses are affected by the copper content in matte, which is determined by the oxidizing conditions of melting (partial pressure of oxygen), temperature and slag composition. When the matte composition is constant (the requirements for which are largely determined by specific production conditions, for example, the conditions of matte conversion, the presence and type of depletion of slags, etc.) and the melting temperature (temperature constancy is one of the main requirements for maintaining process stability), the main factor determining the loss of nonferrous metals with slag is the composition of the slag. In this case, the composition of the slag affects both dissolved and mechanical losses. Therefore, the article focuses on obtaining generalized (reflecting the total change in dissolved and mechanical losses) dependences of the metal distribution coefficients on the composition of the slag.

Studies of the structure of current industrial slags of the BCS, the proportion and structure of mechanical inclusions of matte in them and the effect on the completeness of the separation of slag and matte under melting conditions and in an electric sump using data on the viscosity of the slag are planned to be carried out at the following stages of work.

To simplify the prediction of the behavior of Cu, Au, and Ag between matte and slag, depending on the composition of the slag, it is advisable to use multiple regression Equations 10–12, presented as follows:

$$L_{Cu} = 162.09 - 31.35 \times FeO/SiO_2 - 4.92 \times CaO, r = 0.58 \quad (10)$$

$$L_{Au} = 185.77 - 29.37 \times FeO/SiO_2 - 6.53 \times CaO, r = 0.54 \quad (11)$$

$$L_{Ag} = 67.56 - 14.08 \times FeO/SiO_2 - 2.11 \times CaO, r = 0.59 \quad (12)$$

The graphs (Figure 2) show the dependences of the distribution of Cu, Au and Ag on the ratio of $FeO/SiO_2$ at a constant concentration of CaO in the slag (10% by weight). The obtained mathematical models adequately describe the production data and can be used in technological calculations.

The analysis shows that the distribution coefficients of copper (Figure 2a) and gold (Figure 2b) change insignificantly with an increase in the ratio of $FeO/SiO_2$ in the slag, which is reflected in the gentle nature of the curves. The patterns of silver distribution are somewhat different. An increase in the $FeO/SiO_2$ ratio in the slag leads to a significant decrease in the silver distribution coefficient (Figure 2c).

The identified trends correspond to theoretical concepts of autogenous smelting and can be explained as follows.

In autogenic melting, the main role is played by redox processes. The distribution of precious metals between matte and slag is largely determined by the metal's affinity for sulfur or oxygen. Copper and gold, exhibiting a greater affinity for sulfur, predominantly concentrate in the matte, while silver, having a more pronounced affinity for oxygen, can transition more significantly into the slag, especially with an increase in the basicity of the slag, reflected by the $FeO/SiO_2$ ratio.

An increase in the $FeO/SiO_2$ ratio in the slag increases the activity of iron oxide (FeO) by increasing the partial pressure of oxygen in the system. This creates favorable conditions for the oxidation of silver and its transition into the slag phase as oxide ($Ag_2O$). Copper and gold, forming more durable sulfides, remain mainly in matte. This explains the slight change in their distribution coefficients when the $FeO/SiO_2$ ratio changes. The transition of gold to slag is caused by its losses due to mechanical losses of matte suspensions of matte in the slag, which did not have time to settle in the bottom phase (matte).

In real slag melts, the fayalite phase ($2FeO \cdot SiO_2$) prevails. From a theoretical point of view [7, 8], when the relation about: Si = 2, the $SiO_2$ lattice is an infinite three-dimensional grid composed of $SiO_4$ silicon-oxygen tetrahedra with common vertices. In this case, all valences of oxygen and silicon are completely mutually saturated. The presence of other oxides in metallurgical slags increases the O:Si ratio. As a result, the ordered silicon–oxygen grid breaks and complex silicon-oxygen anions of the $Si_xO_y^{z-}$ type are formed. Having varying degrees of complexity, silicon–oxygen anions dissociate in the presence of basic oxides according to the scheme: $Si_6O_{18}^{12-} \rightarrow Si_4O_{12}^{8-} \rightarrow Si_3O_9^{6-} \rightarrow Si_2O_7^{6-} \rightarrow SiO_4^{4-}$. For this reason, isolated $SiO_2$ molecules cannot be detected in industrial slags. The described mechanism of formation of silicon-oxygen anions determines the change in the physico-chemical properties of slags and the total loss of non-ferrous metals with slag. It can be seen that with an increase in the $SiO_2$ content in the slag, copper losses with the slag decrease. This phenomenon can be interpreted based on the following considerations.

An increase in the $SiO_2$ content in the slag leads to the formation of Si-O anionic complexes, the presence of which reduces the ion exchange of electrons through the phase boundary of matte and slag. In this case, there is an increase in the surface tension of the matte at the slag boundary layer. An increase in the $SiO_2$ content in the slag increases the likelihood of phthalite formation and leads to a rupture of the silicon-oxygen network structure. This reduces the viscosity of the slag [7, 8]. As a result of these conditions, the coalescence of dispersed matte copper droplets in the slag improves and the mechanical losses of metals in the form of MeS decrease.

The effect of CaO on the distribution of metals is also associated with changes in $FeO/SiO_2$ in the slag. The growth of strong modifier cations ($Ca^{2+}$) in the slag leads to the destruction of the structure of the silica-oxygen network and a decrease in the viscosity of the slag [7]. At the same time, the mechanical losses of copper with slag decrease. This leads to a reduction in the total loss of copper with slag. An increase in the CaO content reduces the activity of silica ($SiO_2$). At the same time, the solubility of copper and gold sulfides in the slag decreases. This facilitates the transfer of copper and gold to matte.

The physical meaning of the $FeO/SiO_2$ ratio, reflecting the basicity of the slag, indicates that

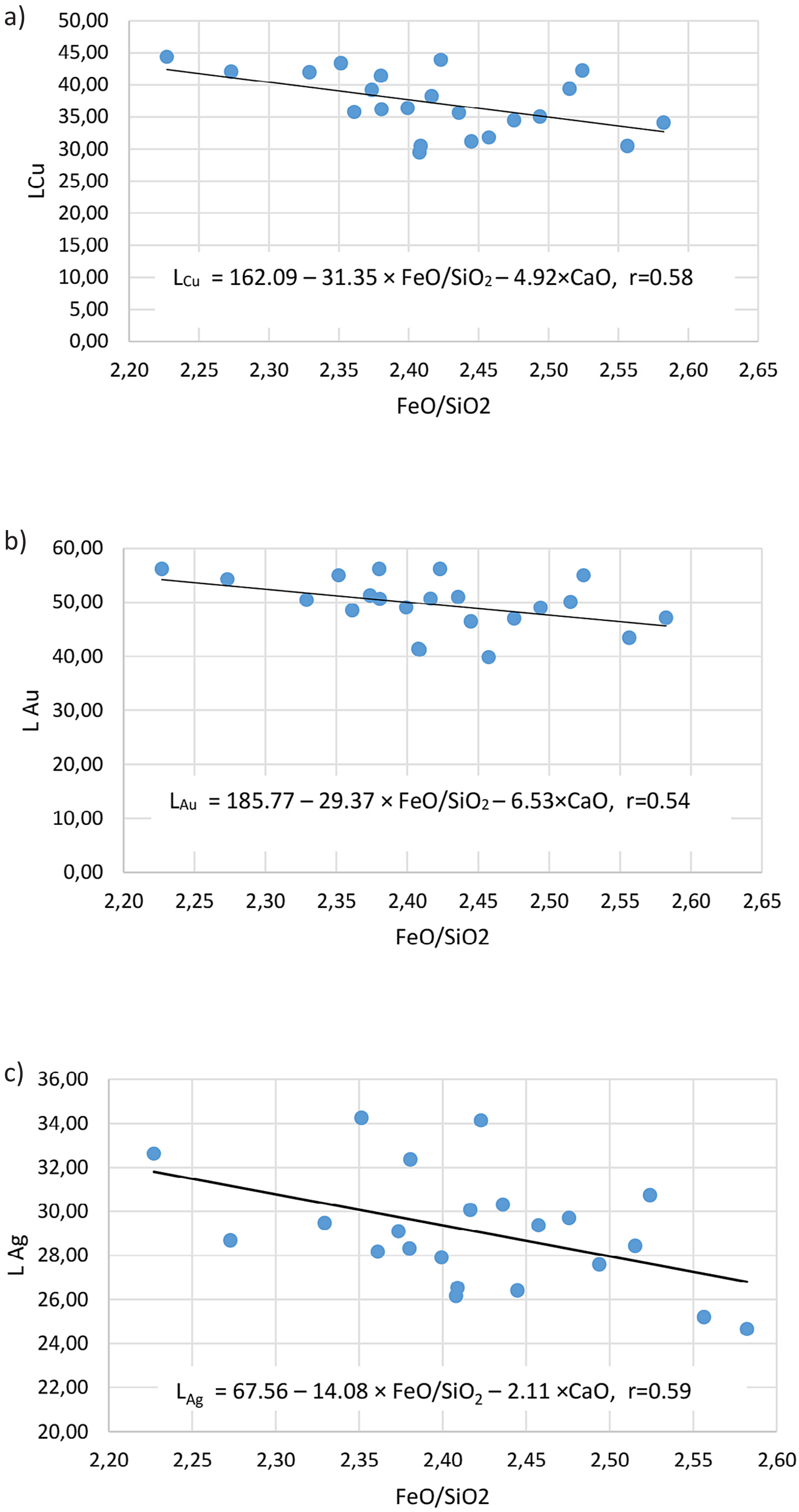


**Figure 2.** Dependence of the distribution coefficient of copper (a), gold (b) and silver (c) between matte and slag on the ratio of $FeO/SiO_2$ in the slag: • – industrial data; a straight line – according to the regression equation

a high $FeO/SiO_2$ ratio characterizes more basic slags, while a low one characterizes more acidic ones. The slight change in $L_{Cu}$ and $L_{Au}$ with the change in $FeO/SiO_2$ and the gentle nature of the curves for Cu and Au indicate that the distribution of these metals is relatively less sensitive to changes in slag basicity in this range. This may mean that other factors, such as the concentration of ZnO, have a stronger effect.

A significant decrease in $L_{Ag}$ with an increase in $FeO/SiO_2$ indicates that silver is more actively converted into matte with an increase in slag basicity (high $FeO/SiO_2$). This may be due to the fact that, as already mentioned, FeO can promote the formation of silver complexes in the slag, which leads to an increase in the transition of silver to slag. However, in this case, an increase in $FeO/SiO_2$ shifts the equilibrium towards the matte. Perhaps, in more basic slags, silver forms compounds that are more stable in matte. A change in the viscosity of the slag with a change in $FeO/SiO_2$ can also affect the kinetics of silver distribution.

Thus, the developed multiple regression Equations 10–12 make it possible to take into account the influence of the main slag components (FeO, $SiO_2$, CaO) on the distribution of Cu, Au, and Ag between matte and slag. The good consistency of the data with the results of [11, 18] and the connections of precious metals with matte inclusions emphasize the importance of taking into account not only the equilibrium distribution, but also the mechanical inclusions of matte in the slag. These inclusions may contain significant amounts of precious metals and affect the overall recovery rate.

Thus, the developed multiple regression Equations 10–12 make it possible to take into account the influence of the main slag components (FeO, $SiO_2$, CaO) on the distribution of Cu, Au, and Ag between matte and slag and are in good agreement with the data from [4, 11]. These equations can be used to optimize the technological parameters of autogenous smelting in order to increase the extraction of precious metals into the matte and minimize their losses with slag. Further research may be aimed at studying the effect of temperature on the distribution of metals.

The initial data and the results obtained will not be directly applicable to the melting process with a new charge mixture. Nevertheless, it is expected that the proportions of metals and slag-forming elements in the smelting products from the new mine will be within the limits comparable to those observed with the use of current raw materials.

The practical value of the presented work lies in the possibility of improving the melting process on matte. The created models make it possible to predict the loss of copper and related metals with slag, depending on the composition of the slag. This allows you to quickly adjust the technological parameters to increase the extraction of valuable components and reduce the negative impact on the environment.

The results of the study will be used to develop recommendations for optimizing the charge, regulating the temperature regime and the composition of the gas phase. The implementation of these recommendations will contribute to increasing the economic efficiency of copper production by reducing the loss of valuable metals with slag. For the successful application of the proposed recommendations, it is necessary to conduct a series of industrial tests. These tests will allow us to confirm the accuracy of the developed models in real production conditions and clarify the optimal technological parameters of melting for a specific charge composition. An important step is the monitoring and analysis of the melting results using a new charge composition, including the control of the composition of slag, matte and exhaust gases. The collected data will allow us to evaluate the effectiveness of optimization and make the necessary adjustments to the technological process.

The effect of changes in the charge composition on other technological parameters should also be taken into account: the viscosity of the slag, the condition of the furnace lining and the formation of dust. These parameters may require additional optimization to ensure stable and efficient operation of the melting unit. In particular, changes in the viscosity of the slag can affect the rate of phase separation and loss of metals with the slag.

Special attention should be paid to the development of a system for operational control and management of slag composition. This system should provide the ability to adjust the composition of the charge in real time. This requires the introduction of modern analysis methods, such as X-ray fluorescence analysis, which allow rapid analysis of the composition of slag and matte.

The implementation of the developed models and recommendations will increase the economic efficiency of copper production and reduce the negative impact on the environment by reducing emissions of harmful substances from exhaust gases and the volume of waste slag. This meets modern requirements for the sustainable development of the mining and metallurgical industry.

## CONCLUSIONS

The effect of slag composition on the distribution of Cu, Pb, As, Au, and Ag between matte and slag during melting of a complex copper-containing charge is studied, as well as the creation of mathematical models for predicting this distribution.

The novelty of the work consists in a comprehensive study of the distribution of a wide range of valuable and related elements, including precious metals, under conditions of smelting at the BCS, taking into account the specifics of raw materials and technological parameters. Mathematical models have been created that predict the distribution of metals (Cu, Pb, As, Au, Ag) between matte and slag, taking into account the composition of the slag and allowing optimizing technological parameters. The developed models make it possible to predict the loss of metals with slag and adjust technological parameters to increase the extraction of valuable components and reduce environmental impacts. The integration of the models into the process control system at the BCS will allow for the transition to scientifically based melting control.

The results of the study will be used to develop recommendations for optimizing the charge, temperature regime and composition of the gas phase. For the successful application of the recommendations, it is necessary to conduct industrial tests and monitor the results.

It is important to take into account the effect of changes in the charge composition on other technological parameters, such as the viscosity of the slag, the condition of the furnace lining and the formation of dust. It is necessary to develop a system of operational control and management of the slag composition using modern methods of analysis.

The implementation of models and recommendations will increase economic efficiency and reduce the negative impact on the environment.

Further development of modeling may include consideration of hydrodynamic factors and the development of three-dimensional models.

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