3D computer model of the Co-Cu-CoS-Cu$_2$S subsystem T-x-y diagram above 800°C
V. I. Lutsyk a,b,* , V. P. Vorob'eva a, A. E. Zelenaya a, M. V. Lamueva a

a Institute of Physical Materials Science, Siberian Branch, Russian Academy of Sciences, Ulan-Ude, Russia
a Banzarov Buryat State University, Chemical Department, Ulan-Ude, Russia

* vluts@ipms.bscnet.ru

(Received 07 March 2019; Accepted 30 March 2021)

Abstract
The three-dimensional computer model of the Co-Cu-CoS-Cu$_2$S subsystem T-x-y diagram at temperatures above 800°C is represented. It is shown that the liquid immiscibility in the binary subsystem Cu-Cu$_2$S is transformed within the ternary system with Co into the wide two-phase region of two immiscible melts, which interrupts the univariant curve of the Co and Cu$_2$S co-crystallization. The special features of the structure of the solidus surface of cobalt, caused by liquid-phase immiscibility are considered.

Key words: Phase diagrams; Immiscibility; 3D visualization; Metal-sulfide systems; Alloys of cobalt and copper

1. Introduction
This work is carried out within the framework of the study of three- and four-component systems, which form the five-component Fe-Ni-Co-Cu-S system.

Investigation of this quinary system was declared in the title of the paper [1], but really the study was limited by the only quaternary system Fe-Ni-Cu-S and ternary systems on its borders. As for the systems with cobalt, the only Co-S binary system was discussed. Generally, many publications are devoted to the Fe-Ni-Cu-S system, for instance [1-3]. It is possible especially to name among them the papers [2] and [3], because besides the detailed description of experiments, results are represented in the form of three-dimensional (3D) isothermal sections (which occurs infrequently); six isothermal sections in the diapason 700-1200°C in the limited region of concentrations (up to 10 % weight Fe) [2] and 3D isothermal sections at 1000°C, 850°C and 400°C [3].

Furthermore, the theoretical analysis of the Fe-Ni-Cu-S system for the processes of the quasi-equilibrium directional solidification of the four-component melt was carried out [4, 5] and the relationship between the phase diagram and the formation of primary zones in a directionally solidified material was examined [6].

All ternary systems, forming the Fe-Ni-Cu-S system, were thoroughly studied in [7], and the results of these experimental studies were represented in the form of the concentration projections of the surfaces of liquidus and solidus (and the ruled surfaces, produced by their intersection) with isothermal lines.

Among other four-component systems, which form the mentioned above five-component one, it is possible to name the papers, devoted to the Fe-Ni-Co-Cu [8] and Fe-Ni-Co-S [8, 9] systems. Information about the results of experimental study and thermodynamic calculations of the Ni-Cu-S system phase diagram can be found in [10-13] and of the Fe-Cu-S system – in [14-16].

1 Russian Foundation for Basic Research, the project 17-08-00875-a "Assembling of computer 4D models of T-x-y-z diagrams, forming the quinary Fe-Ni-Cu-Co-S system, for the modernization of technological processes of nickel, cobalt and copper production"
Only isothermal sections at 400-900°С in the Co-Cu-S system are represented in [17], but problems of the liquid immiscibility were not discussed there.

Authors of [7], studied in detail the ternary systems on the boundaries of the Fe-Ni-Cu-S system, now carry out the analogous studies of the Fe-Co-Cu-S system [18-20].

However, the main problem and the main difficulties both in experimental results representation and in phase diagrams of ternary and quaternary systems computer simulation are caused by the liquid immiscibility in the binary Cu-S system. Immiscibility in the ternary system, formed by the Cu-Cu₂S binary with Ni, produces the univariant monotectic transformation, and with Fe or Co – the invariant one. Unfortunately, there are practically no theoretical works, devoted to the influence of the liquid immiscibility on the geometric structure of T-x-y and T-x-y-z diagrams of three- and four-component systems [21].

The most complete review of T-x-y diagrams with melt immiscibility can be found in the monograph [22]. It has examples of nine eutectic type diagrams with immiscibility. Five of them are formed by one, two, or three binary systems with monotectic, where a dome of immiscibility: 1) occupies part of one liquidus field; 2) starts from the binary liquidus and crosses the univariant curve between the two liquidus fields; 3) crosses two fields of liquidus; 4) exists in all three liquidus fields, forming a complex structure of the phase region with three liquids. Four more examples are given for an eutectic system, in which the dome above two liquid phases does not connect the binary systems, but exists in one, two, three fields of liquidus, crossing, respectively, one, two or three univariant curves. In monographs [23, 24], the system made up of binary ones was discussed: with continuous rows of solid solutions, eutectic and monotetic. As for the diagrams, described in [22], the most discussed in other monographs [23, 25-27] is a diagram with an invariant monotectic equilibrium.

However, the works [22-27] is not free from flaws. Some of them are mentioned in [28]. It is also important to emphasize that the surface of solidus, which is conjugated to the surface of liquidus, into which the immiscibility dome is entering, has geometric features, which are referred to, for example, [29, 30].

Therefore it is convenient to use the spacious (3D – for ternary and 4D – for quaternary systems) computer models of phase (T-x-y, T-x-y-z) diagrams for visualization and better understanding of obtained experimental data and general geometric construction of some phase diagrams for specific systems.

The basic approach to construct the spatial models of isobaric phase diagrams of three-component systems is that each of these models is a geometric object of three-dimensional (3D) space in the coordinates of the temperature-concentration (T-x-y), composed of non-ruled and ruled surfaces. Ruled surface is generated by a forming horizontal segment and two directing curves, and bounds the corresponding three-phase region. All other surfaces (liquidus, solidus, solvus, transus, etc.) are the non-ruled ones.

It is obvious that the principle of the ruled surface formation corresponds to the kinematic way of its origin. However, this method allows generate adequately the non-ruled surface as the forming element moving along the directing ones too. Only in this case there are no requirements to the forming element to be straightforward. In cases, when the kinematic method cannot "cover" the entire surface (for example, if there are folds or holes), it is broken into fragments. Then the problem of the surface adequate presentation is connected with its gluing from fragments, with obligatory control by equating derivatives in the places of gluing.

The technology of PD spatial models creating from its geometric elements (surfaces or phase regions) is implemented in the author's program Phase Diagrams Designer [31].

Papers, cited above, include isothermal sections (three-dimensional sections for the four-component Fe-Ni-Cu-S system [2, 3]) and sometimes the projection of liquidus [13] and even liquidus and solidus surfaces [7, 18-20]. This limited information does not give the possibility to obtain the phase diagram as a whole, since entire enormous volume of the carried out experimental work does not brought to the total space model, which would make it possible to construct any arbitrarily given sections and to perform the calculations of the mass balances of
Figure 1. Binary systems Co-Cu (A-B) (a), Co-CoS (A-R1) (b), Cu-Cu₂S (B-R2) with an enlarged fragment of the phase regions L1+R2 and L2+B (c), the quasi-binary section CoS-Cu₂S (R1-R2) (d), forming the subsystem Co-Cu-CoS-Cu₂S (A-B-R1-R2)
2. Initial experimental data

Binary systems are well studied and reference books data of their phase diagrams can be confidently used [32-34] (Figure 1).

Investigation of the Co-Cu-S system (the Co-Cu-CoS-Cu$_2$S subsystem) is limited in the current research in concentration - by the quasi-binary section CoS-Cu$_2$S and in temperature - by 800°C (Figure 2).

Design of 3D computer model requires re-designation of initial components and compounds [31]: Co, Cu, CoS, Cu$_2$S, Co$_3$S$_3$ as A, B, R1, R2, R3, correspondingly, and then of the basic points, which form the phase diagram (Table 1-2). For instance, designations e$_{BR2}$, B$_2$, R$_2$S correspond to the apexes of the invariant complex in the binary Cu-S system (the Cu-Cu$_2$S or B-R2 subsystem), i.e., to phases L, Cu (B), Cu$_2$S (R2), participating in the eutectic L→Cu+Cu$_2$S (e$_{BR2}$: L→B+R2) reaction.

The binary Co-Cu (A-B) system is the usual peritectic system with one transformation L+Co→Cu (p$_{AB}$: L+A→B) at 1112°C (Figure 1a). It is characterized by the variable solubility of Cu in α-Co. It is observed a "retrograde" view of the solidus in the temperature range 1112-1495°C, when the solubility of copper in the solid solution first grows with an increase of temperature, and then it decreases and has a maximum at 1367°C and the concentration of copper 20.8% weight.

The compound Co$_{0.13}$S (R1) is melted congruently at the temperature 1182±1°C and is characterized by the region of the homogeneity in the range of concentrations 35.5-40% weight of sulfur.

The incongruently melting compound Co$_4$S$_3$ (R3) is forming in the binary Co-CoS (A-R1) subsystem as a result of the peritectic L+CoS→Co$_4$S$_3$ (p$_{R1R3}$: L+R1→R3) reaction at 930°C. The eutectic L→Co+Co$_4$S$_3$ (e$_{AR3}$: L→A+R3) reaction at 872°C is observed also (Figure 1b).

The second binary sulfide Cu-Cu$_2$S (B-R2) subsystem is characterized by the liquid immiscibility region mkn and the monotectic L1→L2+Cu$_2$S (m(n): L1→L2+R2) at 1105°C and eutectic L→Cu+Cu$_2$S (e$_{BR2}$: L→B+R2) at 1067°C reactions (Figure 1c).

High-temperature part of the quasi-binary section CoS-Cu$_2$S (R1-R2), constructed experimentally [18], shows the eutectic equilibrium L→CoS+Cu$_2$S (e$_{R1R2}$: L→R1+R2) at 941°C (Figure 1d).

The ternary Co-Co-Cu-CoS-Cu$_2$S (A-B-R1-R2) subsystem is characterized by the wide region of liquid-phase immiscibility (Figure 2). The critical point K of the immiscibility region has the temperature 1334°C. Tie-lines (K is their degeneration) on the border of the immiscibility region are isotherms, which form two ruled surfaces as the boundaries of three-phase monotectic reactions with participation of either Co (L1→L2+Co and directing lines KN and KM) or the solid solution on the base of Cu$_2$S (L1→L2+Cu$_2$S and directing lines nN and mM). The thermal analysis showed the temperature 1076°C of the four-phase invariant monotectic transformation L1→L2+Co+Cu$_2$S (M(N): L1→L2+A+R2) [18]. Besides, the subsystem includes two invariant transformations of quasi-peritectic type L+CoS→Cu$_2$S+Co$_3$S$_3$ (Q$_1$: L+R1→R2+R3) at 875°C, L+Co→Cu+Cu$_2$S (Q$_2$: L+A→B+R2) at 1070°C and one invariant transformation of the eutectic type L→Co+Cu$_2$S+Co$_3$S$_3$ (E: L→A+R2+R3) at 837±2°C. Since the reaction Q$_2$ temperature is not experimentally determined and is indicated only in the temperature interval 1067-1076°C [18], that it is accepted equal to 1070°C in the 3D model.

Concentration coordinates of the apexes of complexes, which correspond to quasi-peritectic Q$_1$ and Q$_2$ reactions, are cited in [18] such, that the points Q$_1$ and Q$_2$, corresponding to liquid concentrations, occur within R$_1$Q$_1$R$_2$Q$_3$Q$_1$ and A$_{Q2}$B$_{Q2}$R$_{Q2}$ triangles, and they correspond to not quasi-peritectic Q$_1$: L+R1→R2+R3 and Q$_2$: L+A→B+R2 reactions, but to eutectic L→R1+R2+R3 and L→A+B+R2+R3 ones, accordingly. Therefore for the 3D computer model coordinates of the R$_3$Q$_1$ and B$_{Q2}$ points were corrected in such a way that the Q$_1$ and Q$_2$ points would not appear inside the tie-triangle (Table 1).
Figure 2. 3D computer model of the subsystem Co-Cu-CoS-Cu$_2$S (A-B-R1-R2) T-x-y diagram (a) and its x-y projection (b) (3D computer model is constructed down to 800°C (corresponding points below the ternary eutectic E temperature 837°C are noted by the superscript "0")
Table 1. Base points (weight portions), according to which the 3D model of the subsystem Co-Cu-CoS-Cu$_2$S (A-B-R1-R2) has been designed *

| No | Point | $z_i$(Co) | $z_i$(S) | $z_i$(Cu) | T°C | No | Point | $z_i$(Co) | $z_i$(S) | $z_i$(Cu) | T°C |
|----|-------|-----------|-----------|-----------|-----|----|-------|-----------|-----------|-----------|-----|
| 1  | Co (A)  | 1         | 0         | 0         | 1495 | 32 | m    | 0         | 0.015    | 0.985     | 1105 |
| 2  | Cu (B)  | 0         | 0         | 1         | 1084.6 | 33 | n    | 0         | 0.197    | 0.803     | 1105 |
| 3  | CoS (R1) | 0.625     | 0.375     | 0         | 1182 | 34 | R2$_{min}$ | 0         | 0.205    | 0.795     | 1105 |
| 4  | Cu$_2$S (R2) | 0        | 0.205     | 0.795    | 1131 | 35 | k    | 0         | 0.088    | 0.912     | 1510 |
| 5  | p$_{AB}$ | 0.051     | 0         | 0.959     | 1112 | 36 | e$_{R1R2}$ | 0.270    | 0.293    | 0.437     | 941  |
| 6  | A$_B$   | 0.873     | 0         | 0.127     | 1112 | 37 | R1$_{R2}$ | 0.480    | 0.361    | 0.159     | 941  |
| 7  | B$_A$   | 0.086     | 0         | 0.914     | 1112 | 38 | R2$_{R1}$ | 0.084    | 0.232    | 0.684     | 941  |
| 8  | e$_{AR3}$ | 0.734  | 0.266     | 0         | 872  | 39 | e$_{BR2}$ | 0         | 0.007    | 0.9923    | 1067 |
| 9  | A$_{R3}$ | 1         | 0         | 0         | 872  | 40 | B$_{R2}$ | 0         | 0        | 1         | 1067 |
| 10 | R3$_A$  | 0.701     | 0.299     | 0         | 872  | 41 | R2$_B$ | 0         | 0.205    | 0.795     | 1067 |
| 11 | R3$_{1B}$ | 0.714  | 0.286     | 0         | 930  | 42 | M     | 0.074    | 0.016    | 0.910     | 1076 |
| 12 | R1$_{R3}$ | 0.645  | 0.355     | 0         | 930  | 43 | N     | 0.074    | 0.185    | 0.741     | 1076 |
| 13 | R3$_{R1}$ | 0.698  | 0.302     | 0         | 930  | 44 | K     | 0.523    | 0.106    | 0.371     | 1334 |
| 14 | Q$_1$   | 0.614     | 0.270     | 0.116     | 875  | 45 | Q$_2$ | 0.052    | 0.007    | 0.951     | 1070 |
| 15 | R1$_{Q1}$ | 0.653  | 0.337     | 0.010     | 875  | 46 | A$_{Q2}$ | 0.887    | 0        | 0.113     | 1070 |
| 16 | R2$_{Q1}$ | 0.092  | 0.207     | 0.701     | 875  | 47 | B$_{Q2}$ | 0.062    | 0        | 0.938     | 1070 |
| 17 | R3$_{Q1}$ | 0.661  | 0.282     | 0.057     | 875  | 48 | R2$_{Q2}$ | 0.035    | 0.197    | 0.768     | 1070 |
| 18 | E       | 0.642     | 0.246     | 0.112     | 837  | 49 | A$_{M(N)}$ | 0.887    | 0        | 0.113     | 1076 |
| 19 | A$_E$   | 0.934     | 0         | 0.066     | 837  | 50 | R2$_{M(N)}$ | 0.052    | 0.199    | 0.749     | 1076 |
| 20 | R2$_E$  | 0.080     | 0.196     | 0.724     | 837  | 51 | A$_K$ | 0.924    | 0        | 0.076     | 1334 |
| 21 | R3$_E$  | 0.668     | 0.263     | 0.069     | 837  | 52 | max   | 0.240    | 0.180    | 0.580     | 1091 |
| 22 | R1$_{0Q1}$ | 0.590 | 0.361     | 0.049     | 800  | 53 | A$_{Q2}$ | 1        | 0        | 0         | 800  |
| 23 | R2$_{0Q1}$ | 0.119  | 0.208     | 0.673     | 800  | 54 | B$_{Q2}$ | 0        | 0        | 1         | 800  |
| 24 | R3$_{0Q1}$ | 0.631  | 0.307     | 0.062     | 800  | 55 | R2$_{0Q2}$ | 0.560    | 0.167    | 0.273     | 800  |
| 25 | A$_{0B}$ | 1        | 0         | 0         | 800  | 56 | A$_{0R3}$ | 1        | 0        | 0         | 800  |
| 26 | B$_{0A}$ | 0        | 0         | 1         | 800  | 57 | R3$_{0A}$ | 0.750    | 0.250    | 0         | 800  |
| 27 | B$_{0R2}$ | 0        | 0         | 1         | 800  | 58 | R1$_{0R2}$ | 0.540    | 0.381    | 0.079     | 800  |
| 28 | R2$_{0B}$ | 0        | 0.205     | 0.795     | 800  | 59 | R2$_{0R1}$ | 0.005    | 0.264    | 0.731     | 800  |
| 29 | A$_{0E}$ | 1        | 0         | 0         | 800  | 60 | R1$_{0R3}$ | 0.600    | 0.400    | 0         | 800  |
| 30 | R2$_{0E}$ | 0.113  | 0.163     | 0.724     | 800  | 61 | R3$_{0R1}$ | 0.645    | 0.355    | 0         | 800  |
| 31 | R3$_{0E}$ | 0.666  | 0.249     | 0.085     | 800  |    |        |          |          |           |      |

* The lowest temperatures here is 800°C (below the eutectic invariant point E at 837°C); 3D model is constructed down to this temperature and corresponding points are noted by the superscript "0".

** Concentration coordinates of the R3$_{Q1}$ and B$_{Q2}$ points were corrected in such a way that the Q1 and Q2 points would not fall inside the R1$_{Q1}$R2$_{Q1}$R3$_{Q1}$ and A$_{Q2}$B$_{Q2}$R2$_{Q2}$ tie-triangles, accordingly. Coordinates of R3$_{Q1}$ and B$_{Q2}$ points, which correspond to data [18], are indicated in the brackets.
Table 2. Scheme of uni- and invariant states of the subsystem Co-Cu-CoS-Cu$_2$S (A-B-R1-R2) (Figure 2) $^a$, k>A>K>R1>R2>p$_{AB}$>m(n)>B>M(N)>Q2>e$_{BR2}$>e$_{R1R2}$>e$_{AR3}$>Q1>E $^b$

| Co-CoS (A-R1) | Co-Cu-CoS-Cu$_2$S (A-B-R1-R2) | Cu-Cu$_2$S (B-R2) | Co-Cu (A-B) |
|---------------|-------------------------------|------------------|-------------|
| L1$\rightarrow$L2+A | L1$\rightarrow$L2+R2 | L1$\rightarrow$L2+R2 | L2$\rightarrow$A+B |
| KM, KN, A$_R$A$_M$(N) | mM, nN, R$_{2m(n)}$R$_{2M(N)}$ | p$_{AB}$Q2, A$_B$A$_Q2$, B$_BA$Q2 |
| A+B+R2 | L2$\rightarrow$A+R2 | E: L1$\rightarrow$A+R2 |
| A$_{Q2}$A$_0$Q2, B$_{Q2}$B$_0$Q2, R$_{2Q2}$R$_{20Q2}$ | L2$\rightarrow$B+R2 | NE, A$_{M(N)}$A$_E$, R$_{2M(N)}$R$_{2E}$ |
| L1$\rightarrow$L2$\rightarrow$L3 | L1$\rightarrow$L1$\rightarrow$L1+R1$\rightarrow$L1+R1+R2 |
| e$_{R1R2}$Q1, R$_1$R$_2$R$_1Q1$, R$_2$R$_1$R$_2Q1$ | R$_1$R$_2$R$_1Q1$, R$_2$R$_1$R$_2Q1$, R$_1$Q$_1$R$_1^0$Q1, R$_2$Q$_1$R$_2^0$Q1, R$_3$Q$_1$R$_3^0$Q1 |
| Q1: L1$\rightarrow$L1+R1$\rightarrow$L2+R2 | R1$\rightarrow$R2+R3 |
| L1$\rightarrow$L1$\rightarrow$L1$\rightarrow$L1 | Q1E, R$_{2Q1}$R$_2E$, R$_3$Q$_1$R$_3E$ |
| e$_{R3}$E, A$_R$A$_3E$, R$_3$A$_R$R$_3$ | E: L1$\rightarrow$A+R2+R3 |
| A$\rightarrow$R2+R3 | A$\rightarrow$R2+R3 |
| A$_{E}$A$_0$E, R$_2E$R$_20$E, R$_3E$R$_30$E |

$^a$ The lowest temperatures here is 800$^\circ$C (below the eutectic invariant point E at 837$^\circ$C); 3D model is constructed down to this temperature and corresponding points are noted by the superscript "0"  
$^b$ Co (A), Cu (B), CoS (R1), Cu$_2$S (R2), Co$_3$S$_4$ (R3)

3. 3D simulation

3D simulation is carried out into several steps [31]. The scheme of uni- and invariant states (Table 2) is formed firstly. It is the description of uni- and invariant reactions and, correspondingly, of three- and four-phase regions (degenerated into a planar complex).

Further, it is transformed into the three-dimensional form, in which the corresponding ruled surfaces and the isothermal planes, which play the role of the complexes and correspond to invariant reactions, graphically are presented. Then the necessary unruled surfaces (q - liquidus, s - solidus, v - solvus, etc in the 3D model and in the Table 3) are added to these ruled surfaces and planes.

As a result, the prototype of T-x-y diagram is obtained, which is transformed into the real system T-x-y diagram 3D model after the input of the coordinates of all base points and correction of the curvature of lines and surfaces (Figure 2). It is possible to divide the 3D image of the T-x-y diagram (Figure 2) into its constituent ("exploded" [23]) phase regions (Figure 3; Figure 4).

So, the Co-Cu-CoS-Cu$_2$S (A-B-R1-R2) subsystem T-x-y diagram 3D model (Figure 5a; Figure 6a) is well agreed with the experimental data in the liquids (Figure 5b) and solidus (Figure 6b) surfaces, correspondingly. Therefore it can be considered as the qualitative generalization of experimental data and be used as the basis for further study of the system.
Figure 3. Phase regions with the melt (L) of the subsystem Co-Cu-CoS-Cu$_2$S (A-B-R1-R2) T-x-y diagram: two-phase (a) and three-phase regions (b)

The analysis of the T-x-y diagram geometric structure is presented as the scheme of uni- and invariant states (Table 2). Four M(N), Q$_2$, Q$_1$ and E invariant transformations of the Co-Cu-CoS-Cu$_2$S (A-B-R1-R2) subsystem, in accordance with the temperature row, are written to the scheme, where every three-phase reaction has the initial and final points of the interacting phases concentrations. Contours of the unruled surfaces are combined from these lines. For example, $e_{R1R2Q1}$, $R1_{R2}R1_{Q1}$, $R2_{R1}R2_{Q1}$ lines correspond to concentrations change in the liquid (L) and solid (R1 and R2) phases in the $L \rightarrow R1+R2$ reaction.

The $e_{R1R2Q1}$ curve is one of the contour lines of CoS (R1) on the border of two liquidus surfaces, while the $R1_{R2}R1_{Q1}$ curve forms its solidus contour. The $R2_{R1}R2_{Q1}$ curve participates in the shaping of R2 solidus contour. Thus, the scheme makes it possible to determine the types (ruled, unruled, plane, etc) and to calculate number of all surfaces, to indicate their contours and
to describe borders of all phase regions. As a result, the Co-Cu-CoS-Cu$_2$S T-x-y diagram consists of 82 surfaces (Table 3) and 33 phase regions (Table 4; Figure 3; Figure 4).

The 3D model has been constructed on the base of experimental liquidus and solidus surfaces. It consists of the immiscibility cupola, six liquidus and six solidus surfaces of Co (A), Cu (B), CoS (R1), Cu$_2$S (R2), Co$_4$S$_3$ (R3) (where the liquidus and solidus surfaces of Cu$_2$S (R2) are more complex: both surfaces are divided into two parts – "up" and "down" (q$_{R2_{up}}$, q$_{R2_{down}}$, s$_{R2_{up}}$, s$_{R2_{down}}$ in the Table 3).

**Figure 4.** Phase regions without the melt (L) of the subsystem Co-Cu-CoS-Cu$_2$S (A-B-R1-R2) T-x-y diagram: two-phase (a), three-phase (b) & one-phase (c)
Table 3. Surfaces of the T-x-y diagram

| No | Designation | Contour | No | Designation | Contour |
|----|-------------|---------|----|-------------|---------|
|    | liquidus - q |         |    |             |         |
| 1  | qA          | \(Ae_{AB}E_{\text{max}}NKMQ2p_{AB} \) | 4  | qR2,up      | R2nNmaxQ1r1R2r1 |
| 2  | qB          | \(Bp_{AB}Q2e_{BR2} \) | 5  | qR2,down    | e_{BR2}Q2Mm   |
| 3  | qR1         | R1er1R1Q1pr1R3 | 6  | qR3         | e_{AR2}pR1r1Q1E |
| 7  |            |         |    |             |         |
|    | solidus - s |         |    |             |         |
| 8  | sA*         | AAR2AE_{AM(N)}AKQ2A2B | 11 | sR2,up      | R2R2_{min}R2M(N)R2e_{R2,Q1R1}R1 |
| 9  | sB*         | BB_{AB}Q2B_{R2} | 12 | sR2,down    | R2R2_R2_{min}R2M(N)R2e_{R2,Q1R1}R1 |
| 10 | sR1         | R1R1R1Q1R1R3 | 13 | sR3         | R3R3R3R3_{Q1}R3_{E} |
|    |             |         |    |             |         |
|    | solvus - v |         |    |             |         |
| 14 | vAB*        | ABB_{AB}Q2Q2A2B | 21 | vBA*        | B_{AB}B_{AB}Q2Q2 |
| 15 | vAR2        | AAR2A2Q2A2_{R1}AE_{AM(N)} | 22 | vBA2        | R2Q2R2_{Q2,Q1R1}R2M_{(N)} |
| 16 | vAR3*       | AAR2A2R1{e}_{AR2} | 23 | vR3A        | R3R3R3R3_{Q1}R3_{E} |
| 17 | vBR2*       | BR2BR2BR2_{Q2B2Q2} | 24 | vR2B        | R2BR2_{R2,Q1R1}R2B |
| 18 | vR1R2       | R1Q1R1Q1R1_{R2}R1R2r1 | 25 | vR1R1Q1    | R2Q2R2_{Q2,Q1R1}R2r1R2 |
| 19 | vR1R3       | R1R1R1_{Q1}R1_{R2}Q1Q1r1 | 26 | vR1R3Q1    | R2R3R3_{Q1}R3_{Q1}R3_{Q1} |
| 20 | vR2R3       | R2R2BR2Q2Q2Q2Q2 | 27 | vR2R3Q1    | R3R3R3R3_{Q1}R3_{Q1}R3_{Q1} |
|    |             |         |    |             |         |
|    | ruled surfaces - r (types of q, s, v, i [31]) |         |    |             |         |
| 28 | qAB         | pABQ2Q2A2AB | 49 | qBR2       | e_{BR2}Q2B2B2 |
| 29 | qBA         | pABQ2B2Q2B | 50 | qR2B       | e_{R2B}Q2R2_{Q2,R2}B2 |
| 30 | sAB         | A_{AB}Q2B_{AB} | 51 | sBR2       | B_{BR2}B_{R2}Q2R2B2 |
| 31 | qAR2,up     | NmaxE_{AR2}E_{AM(N)} | 52 | qR2R1      | e_{R2R1}Q1R1Q1R1R2 |
| 32 | qR2A,up     | NmaxE_{AR2}E_{R2M(Q2)} | 53 | qR2R1      | e_{R2R1}Q1R1Q1R1R2 |
| 33 | sAR2,up     | Ae_{AR2}EM_{R2M(Q2)R2E} | 54 | sBR2R1    | R1R1Q1R2R2_{Q1}R2Q1 |
| 34 | qAR2,down   | MQ2A2Q2M_{(N)} | 55 | qR3R3      | nR3R1Q1R1Q1R1R3 |
| 35 | qR2A,down   | MQ2R2R2_{Q2M(Q2)R2M(Q2)} | 56 | qR3R3      | nR3R1Q1R3Q1R3R3 |
| 36 | sAR2,down   | A_{Q2}AE_{R2M(Q2)R2M(Q2)R2Q2} | 57 | sR3R3      | R1R1Q1R3Q1R3R3R1 |
| 37 | qAR3        | e_{AR3}A_{AR3} | 58 | qR3R3      | Q1R3R2R2Q2 |
| 38 | qAR3        | e_{AR3}E_{AR3}R3_{E} | 59 | qR3R3      | Q1R3R2R3Q1 |
| 39 | sAR3        | A_{AR3}E_{AR3}R3_{A} | 60 | sR3R3      | R2Q1R2Q2R3R3Q1 |
| 40 | iMNK        | MNK     | 61 | iMR2       | mR2_{R2M(R2M)} |
| 41 | iAMk        | MKAR_{AM(N)} | 62 | iNR2       | nR2_{R2M(R2M)} |
| 42 | iAN         | NAR{AM(N)} | 63 | iMN        | mMN |
| 43 | vR1R2Q1Q1   | R1Q1R1_{Q1}R2Q2r1Q2Q2 | 64 | vBR2Q2      | A_{Q2}Q2B_{Q2}Q2 |
| 44 | vR1R3Q1Q1   | R1Q1R1_{Q1}R2Q3r1Q3Q1 | 65 | vBR2Q2      | A_{Q2}B_{Q2}Q2Q2 |
| 45 | vR2R3Q1Q1   | R2Q2R2Q3r1Q3Q1Q3 | 66 | vBR2Q2      | B_{Q2}B_{Q2}Q2Q2 |
| 46 | vAR2,0E     | A_{Ae}R2e_{R2e}E | 67 | hQ1R1R3R3   | R1Q1R2Q1R3Q1 |
| 47 | vAR3,0E     | A_{Ae}R3e_{R3e}R3 | 68 | hR1R2Q1Q1   | R1Q1R2Q1Q1 |
| 48 | vAR2,0Q     | R2e_{R2e}R3e_{R3e}R3 | 69 | hR1R3Q1Q1   | R1Q1R3Q1Q1 |
|    | horizontal complexes - h |         |    |             |         |

* The \(S_A, S_B \) surfaces of solidus and \(v_{AB}, v_{BA}, v_{AR3}, v_{BR2,down} \) surfaces of solvus merge into the Co-Cu (A-B) face of the prism because of the degeneration of the solidus and solvus lines in the binary subsystems Co-CoS (A-R1) and Cu-CuS (B-R2) (A_{R2} and B_{R2} points have such concentration coordinates, that they fall into the A and B apexes, respectively), and also because of the concentration coordinates of A_{Q2}, A_{E}, B_{Q2} points (Table 1), which fall on the Co-Cu (A-B) face (Figure 2)
Table 4. Phase regions (Figure 3; Figure 4)

| No | Region | Boundary surfaces | Adjacent phase regions |
|----|--------|-------------------|------------------------|
| 1  | L1+L2  | A, A+B, A+L1+R2, A+R2, L1+L2+R2 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 2  | L1+A   | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 3  | L2+A   | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 4  | L2+B   | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 5  | L1+R1  | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 6  | L1+R2  | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 7  | L2+R2  | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 8  | L1+R3  | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 9  | A      | L1+R2, A+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 10 | B      | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 11 | R1     | L1+R2, A+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 12 | R2     | L1+R2, A+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 13 | R3     | L1+R2, A+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 14 | L1+L2+A| A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 15 | L1+L2+R2 | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 16 | L2+A+B | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 17 | L1+R1+R2 | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 18 | L1+R2+R3 | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 19 | L1+R3+R3 | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 20 | L2+R2+R3 | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 21 | L1+R2+R2 | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 22 | L1+R2+R3 | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 23 | L1+R2+R3 | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 24 | A+B    | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 25 | A+R2   | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 26 | A+R3   | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 27 | B+R2   | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 28 | R1+R2  | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 29 | R1+R3  | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 30 | R2+R3  | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 31 | A+B+R2 | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 32 | A+R2+R3| A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |
| 33 | R1+R2+R3 | A+R2, L1+R2, L1+R1+R2, L1+R1+R3, L1+R2+R3 | L1+L2+A, A+L1+R2, R1+R2, R2+R3 |

Earlier the reference book of computer models of T-x-y and T-x-y-z diagrams of the basic topological types has been created [35]. It includes >200 3D models of T-x-y and 7 4D models of T-x-y-z diagrams. Each computer model is the prototype of the phase diagram with corresponding topology. In the case of the Co-Cu-CoS-CuS T-x-y diagram the construction of its 3D model incorporates the templates of the system with the binary incongruently melting compound and of the system with the univariant monotectic immiscibility.
In contrast to the simple surfaces of primary crystallization of copper and R1, R3, the liquidus surface of Co (A) has the complicate contour. It is formed by eight points A, eAR3, E, N, K, M, Q2, pAB (the point "max" denotes the curvature of the NE line and it is not considered in this case as the liquidus surface contour) (Figure 2b).

Since the contour of the Co (A) liquidus is formed by eight points, then the corresponding to it solidus must be given by eight points. However, they are only seven: A, AR3, AE, AK, AM(N), AQ2, AB. Therefore the basic innovation in this type computer models consists of the presence of the AKAM(N) pseudo-fold on this surface of solidus [28-30]. It is the directing curve of two ruled surfaces and it does not influence the smoothness of the Co (A) solidus surface. Its upper AK point has the critical K point temperature in the intersection of the immiscibility cupola with this liquidus surface. Thanks to the fold, the liquidus and solidus become topologically equivalent surfaces, because the AKAM(N) curve is the conjugate one with two parts of the arc NKM.

Figure 5. Liquidus surfaces of the subsystem Co-Cu-CoS-Cu2S (A-B-R1-R2)
(the ruled surfaces with nN-mM and NK-MK directing curves are shown within the cupola):
3D model (a), experimental [18] (b)

Because of the liquid immiscibility to L1 and L2 under the cupula, which intersects the Q2E line of co-crystallization of A and R2 crystals, it is necessary in this, would seem routine, work to distinguish with what precisely liquid, L1 or L2, the Co (A), Cu (B), Cu2S (R2) crystals coexist. Since the monotectic reaction in the binary Cu-Cu2S (B-R2) subsystem is carried out in the form L1 → L2+R2, then it must be the two-phase region L2+R2 in the lower part (between the mM and pABQ2 lines under the qR2_up liquidus surface) and L1+R2 region (under the qR2_down liquidus surface) in the upper part of the Co-Cu-CoS-Cu2S (A-B-R1-R2) subsystem. Corresponding surfaces of liquidus and solidus (borders of Cu2S (R2)) primary crystallization beginning and finishing) are also divided into two parts.
The T-x-y diagram, besides the immiscibility cupola, six liquidus and six solidus surfaces, includes 39 ruled surfaces and 16 planes (simplexes of four complexes), corresponding to Q1, Q2, M(N) and E reactions.

The ruled surfaces with KN, KM, A_K A_M(N) and nN, mM, R_2 m(n) R_2 M(N) directing curves, respectively, serve as boundaries of the three-phase regions L1+L2+A and L1+L2+R2. The group of five three-phase regions includes liquid L1 (L1+A+R2, L1+A+R3, L1+R1+R2, L1+R1+R3, L1+R2+R3) and the group of three three-phase regions includes liquid L2 (L2+A+B, L2+A+R2, L2+B+R2). Liquidus NE, e_{AR3E}, e_{R1Q21}, p_{R1Q21}, Q1E and p_{ABQ2}, MQ2, e_{BQ2Q2} curves are, in particular, the directing lines of ruled surfaces, which serve as boundaries of these regions. Other three three-phase regions are formed in the subsolidus: R1+R2+R3, A+B+R2, A+R2+R3 below, correspondingly, Q1, Q2, E planes.

The T-x-y diagram is examined in this paper from the highest 1510°C temperature down to 800°C. This boundary for the 3D model is selected conditionally in order to show only all phase transformations with the participation of liquid, and also phase transformations in the subsolidus, connected with the Q1, Q2, E invariant reactions. Therefore there are only 14 solvus surfaces in the temperature interval 837-800°C (Table 3).

After transformation of the scheme of uni- and invariant states from the tabular form into the graphic one, when the horizontal (isothermal) planes, corresponding to the M(N), Q1, Q2, E invariant reactions, and the ruled surfaces are designed, the T-x-y diagram prototype is obtained. It is converted into the real system T-x-y diagram 3D model, when concentrations and temperatures of base points (Table 1) are introduced, and the curvature of lines and surfaces is specified. Comparison of the 3D model (Figure 5a) and experimental [18] (Figure 5b) isothermal

Figure 6. Surfaces of solidus and adjoining it ruled surfaces of the subsystem Co-Cu-CoS-Cu2S (A-B-R1-R2): 3D model (a), experimental [18] (b)
lines on the liquidus surfaces shows that the model line 1335°C adjoins the critical point K, and this is correct, because the temperature of this point is equal to 1334°C, however, experimental line passes far from this point K.

There are considerable disagreements according to the form of the isothermal line 1080°C on the liquidus surface of Cu$_2$S (R2). The 3D model of this surface includes two lines at 1080°C. The first one is located around the N point, since the temperature of the N point is equal to 1076°C (Figure 5a). The second line at 1080°C is located between the NmaxE (in the temperature interval of 1076-1091-837°C) and Cu$_2$S-e$_{R1R2}$ (1131-941°C) lines. As for the experimental version the isothermal line (1080°C), it is located around the point of maximum with 1091°C (Figure 5b). But it is impossible, as the temperature 1080°C is on the Cu$_2$S-e$_{R1R2}$ line.

A main difference in the 3D model (Figure 6a) and experimental (Figure 6b) isothermal lines of the solidus surfaces and connected with them ruled surfaces is caused by the already discussed above contradictions in the concentration coordinates of the apexes of the complexes, which correspond to the Q1 and Q2 quasi-peritectic reactions (Table 1).

As a whole it is possible to consider that the 3D computer model adequately reproduces experiment, and therefore it can be used in the practical work, in particular, for designing any isopleths. For instance, two isopleths have been designed: parallel to the sides Co-Cu (A-B) S$_1$(0.85, 0.15, 0)-S$_2$(0, 0.15, 0.85) (Figure 7a) and CoS-Cu (R1-B) (Figure 7b). Three-phase regions L1+L2+R2, L2+A+R2, L2+B+R2 in these sections merge in the line because of the close arrangement of points and small temperature differences in the angle of copper.

![Figure 7](image_url)

**Figure 7.** Isopleths S$_1$(0.85, 0.15, 0)-S$_2$(0, 0.15, 0.85) (a) and CoS-Cu (b) of the subsystem Co-Cu-CoS-Cu$_2$S (A-B-R1-R2) T-x-y diagram 3D computer model

### 4. Conclusions

The obtained 3D computer model of the Co-Cu-CoS-Cu$_2$S subsystem T-x-y diagram has been designed on the base of the experimental liquidus and solidus surfaces isotherms at temperatures from 1510°C to 800°C. It consists of 82 surfaces and 33 phase regions. The model corresponds to the experimental data and makes it possible to visualize (rotation of 3D figures, x-y projections, any section) not only liquidus and solidus surfaces, but also other surfaces and
phase regions, to understand the crystallization processes and to calculate the masses balances of
the coexisting phases in each of their stages.

Acknowledgement
This work has been performed under the program of fundamental research SB RAS
(project 0336-2019-0008) and was partially supported by the Russian Foundation for Basic
Research (project 19-38-90035).

References
[1] F. Kongoli, Y. Dessureault, A. D. Pelton, Metall. Mater. Trans. B, 29(3) (1998) 591-
601, https://link.springer.com/journal/11663/29/3.
[2] W. Viljoen, Phase Relations in the System Cu-Fe-Ni-S and their Application to the
Slow Cooling of PGE Matte, University of Pretoria, Pretoria, 2001, https://repository.up.ac.za/bitstream/handle/2263/28674/Complete.pdf?sequence=5
[3] V. Raghavan, J. Phase Equilib., 25(5) (2004) 458-461, doi: 10.1361/15477020421188.
[4] V. I. Kosyakov, E. F. Sinyakova, Inorg. Mater., 48(7) (2012) 671-675, doi:
10.1134/S0020168512060076.
[5] E. Sinyakova, V. Kosyakov, G. Palyanova, N. Karmanov, Minerals, 9(9) (2019) 531
(18 pages), doi: 10.3390/min9090531.
[6] V. I. Kosyakov, E. F. Sinyakova, Inorg. Mater., 47(6) (2011) 660-664, doi:
10.1134/S002016851105013X.
[7] R. V. Starykh, S. I. Sineva et al, Russ. Metall., 3 (2009) 263-270, doi:
10.1134/S0036029509030136; 5 (2009) 447-453, doi: 10.1134/S0036029509050164; 5 (2010)
448-455, doi: 10.1134/S0036029510050162; 11 (2010) 1025-1031, doi:
10.1134/S0036029512030135.
[8] V. I. Lutsyk, V. P. Vorob’eva, A. E. Zelenaya, Adv. Mater. Letters, 10(1) (2019) 53-
57, doi: 10.5185/amlett.2019.2172.
[9] V. I. Lutsyk, V. P. Vorob’eva, Rus. J. Phys. Chem., 91(13) (2017) 2593-2599, doi:
10.1134/S0036024417130131.
[10] W. J. Schlitt, R. H. Craig, K. J. Richards, Metall. Mater. Trans. B, 4(8) (1973) 1994-
1996, https://link.springer.com/journal/11663/4/8/page/2.
[11] S. L. Lee, M. J. Larrian, H. H. Kellogg, Metall. Mater. Trans. B, 11(2) (1980) 251-
255, https://link.springer.com/journal/11663/11/2.
[12] Y. Y. Chuang, Y. A. Chang, Metall. Mater. Trans. B, 13(3) (1982) 379-385,
https://link.springer.com/journal/11663/13/3.
[13] F. Tesfaye, D. K. Lindberg, P. Taskinen, Proceedings of EPD Congress 2016 (The
Mineral, Metals & Materials Society), 14-18 February 2016, Nashville, USA, p. 29-37.
[14] A. Sugaki, H. Shima, A. Kitakaze, H. Harada, Econ. Geol., 70(4) (1975) 806-823,
doi: https://doi.org/10.2113/gsecongeo.70.4.806.
[15] A. Kitakaze, Mem. Fac. Eng. Yamaguchi Univ., 68(2) (2017) 55(23)-(75)44,
http://www.msoc.eng.yamaguchi-u.ac.jp/research/pdf/6_3.pdf
[16] V. I. Lutsyk, V. P. Vorob’eva, A. M. Zyryanov, S. Ya. Shodorova, Proceedings of
Takanö Intl. Symp. Metals & Alloys Processing (SIPS 2015), 4 - 9 October 2015, Antalya,
Turkey, 2015, p. 305-326.
[17] J. R. Craig, D. J. Vaughan, J. B. Higgins, Econ. Geol., 74(3) (1979) 657-671,
https://doi.org/10.2113/gsecongeo.74.3.657.
[18] M. O. Ilatovskaya, R. V. Starykh, S. I. Sinyova, Metall. Mater. Trans. B, 45(5) (2014)
1757-1768, doi: 10.1007/s11663-014-0096-x.
[19] M. O. Ilatovskaya, R. V. Starykh, Metall. Mater. Trans. B., 46(1) (2015) 243-249,
doi: 10.1007/s11663-014-0202-0.
[20] M. O. Ilatovskaya, S. I. Sinyova, R. V. Starykh, CALPHAD, 59 (2017) 31-39,
http://dx.doi.org/10.1016/j.calphad.2017.07.007.
Figure 1. Binary systems Co-Cu (A-B) (a), Co-CoS (A-R1) (b), Cu-Cu₂S (B-R2) (c), the quasi-binary section CoS-Cu₂S (R1-R2) (d), forming the subsystem Co-CoS-Cu₂S (A-B-R1-R2).

Figure 2. 3D computer model of the subsystem Co-CoS-Cu₂S (A-B-R1-R2) T-x-y diagram (a) and its x-y projection (b) (3D computer model is constructed down to 800°C (corresponding points below the ternary eutectic E temperature 837°C are noted by the superscript "0")

Figure 3. Phase regions with the melt (L) of the subsystem Co-CoS-Cu₂S (A-B-R1-R2) T-x-y diagram: two-phase (a) and three-phase regions (b)

Figure 4. Phase regions without the melt (L) of the subsystem Co-CoS-Cu₂S (A-B-R1-R2) T-x-y diagram: two-phase (a), three-phase (b) & one-phase regions (c)

Figure 5. Liquidus surfaces of the subsystem Co-CoS-Cu₂S (A-B-R1-R2) (the ruled surfaces with nN-mM and NK-MK directing curves are shown within the cupola): 3D model (a), experimental [17] (b)
Figure 6. Surfaces of solidus and adjoining it ruled surfaces of the subsystem Co-Cu-CoS-Cu₂S (A-B-R1-R2): 3D model (a), experimental [17] (b)

Figure 7. Isopleths $S_1(0.85, 0.15, 0)-S_2(0, 0.15, 0.85)$ (a) and CoS-Cu (b) of the subsystem Co-Cu-CoS-Cu₂S (A-B-R1-R2) T-x-y diagram 3D computer model

TABLES CAPTIONS

Table 1. Base points (weight portions), according to which the 3D model of the subsystem Co-Cu-CoS-Cu₂S (A-B-R1-R2) has been designed

Table 2. Scheme of uni- and invariant states of the subsystem Co-Cu-CoS-Cu₂S (A-B-R1-R2) (Figure 2)*, k<A<K>R1>R2>p_{AB}>m(n)>B>M(N)>Q2>e_{BR2}e_{R1R2}>p_{R1R3}>e_{AR3}>Q1>E**

Table 3. Surfaces of the T-x-y diagram

Table 4. Phase regions (Figure 3; Figure 4)