Article

Fundamental Investigation for Processing of Pb-Cu-S-Bearing Materials

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Abstract: The processing of polymetallic materials provides some challenges to every flowsheet. Within Aurubis Cu-Pb-metallurgical flowsheet, a broad range of raw materials and intermediates are processed. Continuous improvements are required to adapt the flowsheet according to the changing material quantity and quality. Therefore, thermodynamic modeling is the desired and most efficient way to conduct scenario analysis. Hence, databases and software are becoming better and better as the acceptance of this method increased. Further understanding is promoted by conducting experimental test work to validate the calculated results. In this research work, the impact of various oxygen potential on the formation of the condensed phases' slag, matte, speiss and crude lead were investigated. A frequent check of slag metallurgy, in particular, the iron and lead concentration, provide feedback if the metallurgical process is operating at the right oxygen potential. Following, the calculated distribution coefficients for Cu, Pb, As, Sb, Sn and Ni between matte/speiss and speiss/lead are discussed.

Keywords: polymetallic; metal processing; electric furnace; secondary; intermetallic alloys; lead; copper; sulfur

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1. Introduction

Aurubis multi-metal's vision is based on a long tradition of the company, founded in 1866 as Norddeutsche Affinerie, and further developed by adopting modern copper smelting and lead smelting technologies for the processing of primary and secondary materials. This includes smelting of copper concentrate, processing of secondaries (residues, slimes, slags) and recycling materials (scrap, shredder material, e-scrap). This broad range of materials contains not only the mentioned base metals but also a number of minor metals that requires to be properly managed to ensure efficient recoveries and quality of the targeted products.

The processing of Pb-Cu-S-bearing materials is at the lead smelter, located in Hamburg, Germany. A schematic flowsheet of the electric furnace is shown in Figure 1. Metallurgical processes which produce a crude lead bullion allows a concentration of a couple of valuables (Precious Metals, Bi, Sb, Sn, Te) within this phase and is explained by Bauer (2011) [1].

Due to the nature of this process, other intermediates will occur, for instance, a matte and a speiss phase. The main purpose of this process is the extraction of copper into the matte which is processed in the primary operation after a converting step. Depending on the feed mixture of the electric furnace, an alloy will coexist which can concentrate significant amounts of Cu, Fe and Ni associated with As, Sb and Sn. The slag has to be managed to minimize metal losses. The flue dust is recycled within the process and the off-gas is treated in the acid plant.

With the growing complexity in feed material, the metallurgy for the electric furnace needs a proper understanding on how to utilize the existing phases and the capabilities of

all following smelting/refining steps. The operational window is set with controlling the most relevant process criteria such as:

- copper to sulfur ratio and the selection of suitable sulfur sources,
- adjustment of speiss-forming agents (As, Sb, Sn and Ni) in feed,
- application of the desired reduction potential,
- process temperature control.

Figure 1. Flowsheet of Aurubis Cu-Pb-S treatment process.

Fundamental knowledge of speiss formation could be applied on various smelting/reduction technologies, for instance, the well-known process for crude lead production from sinter (blast furnace) or by smelting of complex materials (electric furnace, the Russian acronym for “flash-cyclone-oxygen-electric smelting” KIVCET, Quenau-Schuhmann-Lurgi QSL) or within a slag reduction process under very strong reducing conditions for zinc fuming (Top-Submerged-Lance, electric furnace, Imperial Smelting Furnace). However, each furnace operates with a slightly different feed and at various oxygen potentials. This is expressed in the products, for instance, in the lead concentration of the slag, in the copper concentration of the matte (matte grade), in the impurity content of the lead bullion and finally, also in the composition of the alloy or speiss. This phase contains various intermetallic compounds whereas the proportion of (As + Sb + Sn) to (Co + Cu + Fe + Ni + Pb) can lead to a wide range of speiss compositions according to the definition of Kleinheisterkamp (1948) and Zschiesche (2018) [2,3].

A key aspect of the lead smelter is the processing of complex materials. This type of feed is the main source of different minor valuable metals, such as nickel, tin, antimony, bismuth, among others, important for Aurubis multi-metal recovery strategy.

Some key aspects observed at Hamburg operations related to the speiss formation process are the following ones:

- Arsenic (As) is a key element in the formation of speiss, due to its ability to form intermetallic compounds with base metals such as Cu, Ni and Fe and the main amounts of As will be within the speiss and blister copper phase.
- Antimony (Sb) has a slightly different behavior as it will distribute between speiss and crude lead. Some Sb is also reporting to the blister copper phase.
- Tin (Sn) behaves in a similar way to Sb with a weaker tendency to distribute to the lead phase.

Therefore, special attention needs to be given to understand the fundamental aspects associated to speiss formation which serves as motivation for this research work.

2. Understanding Speiss Metallurgy

Zschiesche (2019) summarized the results of the literature review with a focus on speiss and formation of speiss within complex metallurgical processes [4]. Fundamental investigations go back to the 1950s and conclude on the miscibility gap between matte and speiss. Based on that, ternary or quasi-ternary diagrams, e.g., As-X-S, As-X-X-S, As-X-Pb and As-X-Pb-S (X . . . Cu, Fe, Ni, Pb) were used to define different types of speiss [2]. Important publications that linked these results with industrial applications (e.g., different campaigns within the blast furnace process, imperial smelting process) occurred in the 1980s [5,6]. Later, various publications came from Japan and focused on the matte/speiss and lead/speiss equilibrium, especially on the silver and gold deportment [7–10]. There was more work done which explored the possibilities of pyrometallurgical treatment of speiss or copper lead matte to optimize flow of precious metals and to manage the minor elements.

Until today, the transition and evaluation of this aforementioned knowledge to an industrial scale is an aspect which has not been covered well. The difference in speiss type is often explained by the portion of total (As + Sb + Sn) to (Co + Cu + Fe + Ni + Pb). As, Sb and Sn are called speiss-forming agents. The results showed that the affinity of Fe to As is stronger than the case for Cu to As, which explains the formation of FeAs speiss in strong reducing conditions where metallic Fe is present. The role of Ni is an important one due to its larger affinity to As than for Cu. Following this, it seems to be possible to control the Ni deportment within a Pb-Cu process if a certain level of As is in the feed. The solubility of metallic Cu and sulfidic Cu in Ni-arsenides complicates the control of this. The formation of Ni-arsenides is strongly affected by the As and S content in the feed mixture. The S content in the feed determines the Cu extraction and ensures the formation of matte. The more efficiently this takes place, the less metallic Cu is present to form intermetallic compounds (e.g., Cu antimonides) which will increase the total wt.% Cu in the speiss [4].

A highly-enriched metallic copper phase with low copper activity of 0.3 will start to form intermetallic compounds if As, Sb or Sn are present, and this phase is then called Cu-rich speiss. The formation of an iron-rich alloy (dominated by FeAs or Fe₂As) mainly depends on the amount and form of compound of Fe in the feed mixture, the amount of the other minors and the chosen process atmosphere which is characterized also by final Pb content in the slag. The referred blast furnace process will end with 1.5 wt.% Pb which means an Fe activity of about 0.1. Under these circumstances, the formation of an FeAs main alloy seems to be negligible but this changes when the Fe activity increases due to deeper reduction, at least for an activity of 0.5 (Imperial Smelting process) which will promote the formation of a ferrous speiss. Beyond As, Sb and Sn will form intermetallic compounds and become a part of the speiss. Three different operations with speiss production have to be differentiated. Starting with a low Cu activity of 0.15 in the processing of Pb-bearing materials, these speiss are different from the ones produced during the processing of Pb-Cu complex mixture. Then, the activity of Cu is increased and this will lead to an excess of copper in the speiss composition. The current speiss composition of Aurubis lead smelting process in the electric arc furnace is in-line with the so-called area Pb-Cu charges. If the Cu activity further increases, Cu-rich alloys will be formed in Cu-charges and this can be continued until the right corner is reached where a black copper composition will be reached [5].

In addition, the following implications for industrial lead smelting process can be derived from the above analysis:

- The Fe content of the speiss depends on the presence of metallic Fe which can be minimized by controlling the reduction potential of the process.
- A proper Cu extraction by decreasing the Cu activity will decrease the Cu content in the speiss because of less intermetallic Cu compounds with As, Sb and Sn.
- Although the economic improvement is a main criteria for lead smelting processes, the operation with campaigns would be a serious solution to react on varying feed composition and provide a suitable product quality of lead, matte and speiss.

3. Thermodynamic Calculations

Fundamental calculations were conducted with FactSage 7.2 (GTT-Technologies, Herzogenrath, Germany) to describe the operational window of the lead smelting electric furnace. A company internal database was used which was developed within a research consortia work. Results of the experiments which were incorporated in the database were discussed in [11].

As one of most viral control parameters, there is the lead content of the reduced slag. Internal investigations showed that the average Pb in slag is about 2 wt.% whereas 1.6 wt.% are in oxidic form (PbO). This shall serve as an indicator to select the right reduction potential. The slag target temperature is about 1250 °C but due to bath level and furnace design (water cooled bottom), there is a temperature gradient of more than 100 °C between slag and lead at the bottom. The impact of slag temperature and oxygen potential on lead oxide content of slag is calculated in Figure 2. The right upper corner shows a more detailed resolution of the area from $-11 < \log p_{O_2} < -12$.

Figure 2. Impact of process temperature and oxygen potential on lead oxide content of slag.

The operational window for the process can thus already be narrowed down to a reduction potential of $-11 < \log p_{O_2} < -12$. For this range, the lead oxide content of the slag at $\log p_{O_2} -11$ for 1150 °C reaches about 1.78 wt.% (1.65 wt.% Pb). A PbO content of 0.7% was calculated for 1250 °C. Lowering the oxygen potential minimizes the effect of the temperature on lead oxide solubility in slag. At $\log p_{O_2} -12$, the lead oxide content in slag is significantly lower than the assay derived from furnace production sample.

The result of the thermodynamic calculations showed the presence of slag, solids, matte and metal phase at process temperature. So, speiss and crude lead are still one phase and would separate from each other during cooling. To discuss the elemental behavior, the focus is on the metal distribution coefficient:

$$L^{matte/metal} Me = \frac{\text{wt.\% Me in matte}}{\text{wt.\% Me in metal}} \quad (1)$$

When interpreting these results, the above-mentioned boundary conditions and effects of a closed system, i.e., a saturated gas phase, must be included. Due to its strong affinity for sulfur, copper accumulates mainly in the matte phase, although as the atmosphere becomes more reducing, the concentration in the metal phase increases steadily. Tin tends to remain in the matte phase, but the distribution increasingly points toward the metal as the atmosphere becomes more reducing. Arsenic distributes to both the matte and the metal and tends to change significantly toward the metal only at atmospheres $> \log p_{O_2} -11$. Silver shows an increasing concentration in the metal phase over the range of atmospheres and there is an opportunity to collect a higher proportion of silver from the

range $\log p_{O_2} - 10.8$ due to the metal phase increasing in volume. Nickel has a tendency to remain in the metal phase over the entire range, although nickel concentrations in the matte of up to 0.45 wt.% have been calculated. Of speiss-forming agents (As + Sb + Sn), antimony indicates the clearest tendency to become concentrated in the metal phase. Gold exhibits very low matte/metal partition coefficients, which remains constant even through a change in atmosphere. The distribution coefficients are plotted in Figure 3.

Figure 3. Impact of oxygen potential ($\log p_{O_2}$) on the elemental distribution coefficient between matte/metal at $T = 1150\text{ }^{\circ}\text{C}$.

Table 1 summarizes the targeted collector phase for each mentioned element. Circular marks show up where those elements are also concentrated.

Table 1. Overview of targeted element deportment in the molten products of lead smelting electric furnace with X ... target and O ... contained.

Element/Phase	Cu	Pb	Au	As	Sb	Sn	Ni
Slag	-	O	-	-	O	O	-
Matte	X	O	O	O	O	O	O
Metal consists of:	-	-	-	-	-	-	-
Speiss	O	O	O	X	O	O	X
Pb bullion	-	X	X	-	X	X	-

4. Experimental Work

The authors in [12] explained the chosen experimental setup to approach the collection of experimental data to improve the thermodynamic database. The outline of research techniques provides insights in the execution of the test work including the assaying of phases.

Within this research work, a slightly different experimental setup was carried out to conduct a test program in an open system at minimized gas flow rate. This is slightly different to [12], explained by the possibility to control the furnace atmosphere during the holding time as well as the sample drop-off to the water basin for quenching. Figure 4

shows the used components to investigate the chemical reaction between slag, matte, speiss and crude lead at controlled process temperature and furnace atmosphere. In accordance with the explained temperature gradient of the lead smelting electric furnace, 1150 °C is selected as the process temperature for the investigations while the focus is on chemical reactions between matte and metal phase.

Figure 4. Experimental setup to investigate chemical reaction between slag, matte, speiss and crude lead while process temperature and furnace atmosphere could be controlled.

Following the atmosphere prevailing in the electric furnace, this is controlled throughout the experiment with the adjustment of the CO_2/CO concentration and the relation to the oxygen partial pressure:

$$2\{\text{CO}\} + \{\text{O}_2\} = 2\{\text{CO}_2\} \quad (2)$$

$$K = \frac{(p_{\text{CO}_2})^2}{(p_{\text{CO}})^2 \cdot (p_{\text{O}_2})} \quad (3)$$

with the equilibrium constant K at 1150 °C about $K = 4.757 \times 10^{11}$.

$$p_{\text{O}_2} = \frac{(p_{\text{CO}_2})^2}{(p_{\text{CO}})^2 \cdot 4.757 \times 10^{11}} \quad (4)$$

whereby the desired oxygen partial pressure is set by means of the CO_2/CO -ratio. Table 2 shows the required CO_2/CO -ratio to achieve the desired furnace atmosphere ($-10 < \log p_{\text{O}_2} < -12$), calculated at a process temperature of 1150 °C.

The feed material for the tests originates from the production process of the Aurubis lead electric furnace. The material (4 g input) was crushed and milled to meet the requirements for accuracy of weighing (milligrams). The feed mix consists of the following

proportions (75% mixture of slag, matte and speiss and 25% crude lead). Before the start of the test, the feed mix was first analyzed without the lead content to prevent problems during sample preparation. Subsequently, the crude lead portion was included in the overall analysis by calculation. An overview of all analyses can be found in Table 3.

Table 2. CO₂/CO ratios to produce the desired oxygen partial pressure at T = 1150 °C.

Oxygen Potential (pO ₂) in Atm	CO ₂ /CO-Ratio in Gas Flow
9.41582×10^{-11} (log pO ₂ = −10)	6.7
9.49345×10^{-12} (log pO ₂ = −11)	2.1
9.34381×10^{-13} (log pO ₂ = −12)	0.7

Table 3. XRF assay of feed mixture (75% mixture of slag, matte, speiss and 25% crude lead).

As + Sb + Sn Σ wt.%	CaO/SiO ₂ wt.%	Pb/Cu wt.%	Cu/S wt.%	Cu wt.%	Fe wt.%	Ni wt.%	SiO ₂ wt.%	Zn wt.%
1	0.75	4	1.8	7	20	<0.5	12.8	2

To minimize contact with ambient air, the finely-milled feedstock is weighed into an inert mixing chamber according to the specification, and the alumina crucible is sealed in this chamber. In order to reduce idle time and to keep the evaporation of volatile elements like arsenic, bismuth or lead low, the heating from room temperature to target temperature was conducted within 1 h already at desired furnace atmosphere. The residence time of the melt crucible in the tube is about 6 h followed by quenching in a water bath.

After preparing the sample, the half-side of the crucible is selected for assaying within a SEM-EDS system (Jeol JSM-6610, JEOL (Germany) GmbH, Freising, Germany) with a pre-configured EDS from Oxford Instruments (AZtec spectrum analysis, 2019, Oxford Instruments NanoAnalysis, Wiesbaden, Germany). The outer shell of the focused droplets has to have the characteristic spherical shape and a maximum diameter of 100 µm. Thus, a comparability, with respect to the chemical composition of the condensed phases, is aimed. As can be seen in Figure 5, a large number of phases can be identified. Thus, approximately 8–9 analyses (4 phases) are generated per droplet area, i.e., approximately 16–18 analyses per sample. The greatest challenge was the development of a suitable system for the CuPb matte phase. This is characterized by a dark gray matrix which is very rich in Cu, Fe and S, but poor in Pb (spectra 37). However, the white particles must be taken into account, which requires a large-area analysis (rectangles), as in spectra 36 and 38 (Figure 6). A summary of the results can be taken from Table 4.

Figure 5. SEM-EDS photography of the quenched sample (1150 °C, log pO₂ = −12 with 6 h holding time) and the selected fields for assaying the slag phase (39 and 40), the matte phase (36 to 38), the speiss phase (32 and 33) and the crude lead phase (34 and 35).

Figure 6. SEM-EDS analysis for elemental concentration within matte phase in dependence on oxygen potential at $T = 1150\text{ }^{\circ}\text{C}$ and holding time of 6 h (solid) in comparison to results of conducted FactSage calculations (dotted line).

Table 4. SEM results of EDS photography (Figure 5).

Element	32	33	34	35	36	37	38	39	40
	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%
O	3.95	3.09	1.35	1.80	2.05			37.32	36.93
Al								13.79	11.66
Si								9.61	11.21
S			1.19	1.23	20.09	23.94	19.29	0.25	0.25
Ca								8.45	10.60
Fe	0.20	0.39	3.17	3.35	10.94	11.74	11.12	19.24	19.59
Ni	0.07	0.10	27.42	27.14	0.20	0.11	0.53	0.06	
Cu	0.93	1.05	17.56	15.85	46.68	56.40	44.41	0.46	0.66
Zn	0.02	0.00	0.34	0.24	0.71	0.43	0.65	7.51	6.00
As	0.00	0.00	7.13	7.29	0.12	0.00	0.00	0.00	0.00
Sn	0.00	0.27	20.26	20.87	0.40	0.00	0.41	0.18	0.18
Sb	0.25	0.21	14.82	14.99	0.00	0.02	0.00	0.00	0.12
Pb	89.59	89.59	5.31	5.78	15.04	3.53	20.09	0.20	0.37
Bi	4.22	4.51	0.09	0.10	1.14	0.78	1.35	0.10	0.00

Spectra 32 and 33 represents the lead bullion which is characterized by Pb-concentration about 90 wt.%. The darker area around spectra 34 and 35 represent the speiss phase indicated by high concentration of arsenic, antimony and tin. The slag was measured at two spectra (39 and 40) with low Pb-concentration.

5. Results

Data sets from three tests per selected furnace atmosphere ($\log p_{\text{O}_2} -10$, -11 and -12) are available for the evaluation. All tests were performed with identical feedstock,

process temperature and the holding time of $t = 6$ h. The mean values of the main element concentrations formed from the data sets are shown in Figure 6 for the CuPb matte phase and for the slag in Figure 7.

Figure 7. SEM-EDS analysis for elemental concentration within slag phase in dependence on oxygen potential at $T = 1150$ °C and residence time of 6 h (solid) in comparison to results of conducted FactSage calculations (dotted line).

With increasing reduction effect, i.e., from $\log p_{O_2} -10$ to $\log p_{O_2} -12$, both the iron and, moderately, the lead content of the matte phase increase whereas the copper content decreases. The reason for the increasing iron content is the increasing reduction of iron from the slag, which is evident from the absolute concentration but is difficult to read out from the concentration curve. For this reason, the Fe/Pb ratio in the slag was plotted, which, on the one hand, take into account the influence of slag-forming agents such as Al_2O_3 (crucible material) and, on the other hand, at the same time, the decreasing lead concentration (with reducing conditions).

The decreasing lead concentrations with increasing reduction potential becomes obvious. The iron/lead curve is identical with the characteristic of the FactSage results curve. The effect of steadily reducing atmosphere is expressed in the slag only with a moderately lower Fe content, but this change is significant due to the amount of slag. However, Figure 6 shows a clear deviation of the experimentally-determined concentrations of lead, iron and copper, compared to FactSage. While for iron and copper, at least, the trend as a function of $\log p_{O_2}$ fits, the lead concentration seems to be completely different.

One can conclude that experimental setup is capable to reply on varied furnace atmosphere. Somehow, the analysis of the matte phase is quite challenging due to the fact that this phase consists of a matrix and other particles around or within (Figure 5). To tackle this challenge, assaying is done with rectangular objects to cover a wide range and to gather an aggregated information about entire copper lead matte. If selected areas are representative was a key question for this investigation. That is why from each sample, two metal droplets were analyzed and two rectangular fields are covering each phase. With that approach, four assays per phase and, in total, 16 assays are generated per sample.

For this reason, an evaluation with box-plot scheme is the best way to get an indication about the range of deviation. Figure 8 summarizes the copper concentration from three tests equal to 12 assays per element. All in all, copper is from high relevance due to the fact that the lead electric furnace smelting process is conceptualized to extract copper from lead. The tests of $\log p_{O_2} -11$ and -12 seem to have less deviation for the copper concentration measured in the matte. This cannot be confirmed for speiss phase. However, the trend of decreasing copper concentration while becoming more reductive is obvious and could be

shown more clearly than in Figure 6. In accordance with the FactSage calculation, copper is becoming more and more in metal phase while atmosphere is becoming reduced. Due to the very limited solubility of copper in lead, the share of copper in speiss phase increases steadily.

Figure 8. Box-plot for measured copper concentration of the condensed phases in dependence on oxygen potential at T = 1150 °C and holding time of 6 h.

To discuss element department, the calculation of metal distribution coefficients was selected as a proven method. Therefore, the following coefficients were used:

$$L_{metal}^{matte/speiss} = \frac{\text{wt.\% Me in matte}}{\text{wt.\% Me in speiss}} \quad (5)$$

$$L_{metal}^{speiss/lead} = \frac{\text{wt.\% Me in speiss}}{\text{wt.\% Me in lead}} \quad (6)$$

Those coefficients are plotted also in box-plot scheme (Figures 9–12). The coefficient for each sample was determined from the averaged metal concentration of the speiss, matte and lead phases. Thus, three coefficients per element and test are considered. The plots for copper, tin and nickel show a wider range of calculated coefficients than those for the elements of lead, arsenic and antimony. Referring to Figure 9, it can be noted that copper and lead accumulate in the speiss phase as well as in the matte phase. Copper has a tendency to remain in matte phase whereas conditions becoming more reductive in lead tend to deport in speiss rather than remain in matte.

Figure 9. Box-plot for copper and lead distribution coefficient L^{Me} between matte and speiss in dependence on oxygen potential at T = 1150 °C and holding time of 6 h.

Figure 10. Box-plot for arsenic, antimony, tin and nickel distribution coefficient L^{Me} between matte and speiss in dependence on oxygen potential at $T = 1150\text{ }^{\circ}\text{C}$ and holding time of 6 h.

Figure 11. Box-plot for lead distribution coefficient L^{Me} between speiss and crude lead in dependence on oxygen potential at $T = 1150\text{ }^{\circ}\text{C}$ and holding time of 6 h.

Figure 12. Box-plot for copper, arsenic, tin, antimony and nickel distribution coefficient L^{Me} between speiss and crude lead in dependence on oxygen potential at $T = 1150\text{ }^{\circ}\text{C}$ and holding time of 6 h.

Arsenic, antimony, tin and nickel coefficients are < 1 , i.e., they are mainly contained in the speiss phase (Figure 11). The tendency to remain in the speiss phase is not changed by the reducing atmosphere. Figures 11 and 12 show the distribution coefficient between speiss and lead. According to Table 1, it is the target to collect tin and antimony in the lead phase because of given possibilities to extract them into valuable products within the lead refining process. Despite its high solubility in lead, antimony (Figure 12) shows a distribution coefficient $L^{\text{speiss/lead}} \gg 1$ which is because of the mass ratio between speiss and lead, and as a consequence, a high antimony concentration in the speiss. From all speiss forming agents (As, Sb, Sn and Ni), antimony has the highest deportment to the lead phase. Next is tin whereas arsenic and nickel show a stronger tendency to remain in the speiss.

The discussed results underline the importance of carrying out such experiments to validate the information derived from thermodynamic calculations and to analyze the own metallurgical process. The tests at these oxygen potentials will cover a broad range of established technologies starting at $\log p_{\text{O}_2} -12$, which is close to lead blast furnace operation, $\log p_{\text{O}_2} -11$ which is close to Aurubis' secondary smelter and $\log p_{\text{O}_2} -10$ which is close to combined operations (smelting/reducing), for instance, QSL-reactor.

6. Conclusions

In the present paper, the process of Aurubis' lead smelter was explained as well as recent investigations focusing on improved understanding of its complex metallurgy to cope with heterogeneous composite materials and the steadily increasing demand to process low-grade material while keeping the principle of copper and lead separation and, consequently, product quality alive, are discussed.

During the last years, the thermodynamic databases were continuously improved which allows to conduct scenario analysis for the sake of feed mix optimization, product design or to address implications of furnace design. However, Aurubis conducted fundamental investigations which include thermodynamic calculations and laboratory tests with condensed phases. The complexity originated from the initial material requests as well as a complex experimental setup which allows an accurate temperature and oxygen potential control. Furthermore, the quenching of the sample is a huge challenge. A proper assaying to obtain reliable data is another aspect which needs to be mentioned.

Beyond a proper extraction of copper into matte, which has to be managed by adjusting sulfur in the feed material, the selection of the right reduction potential is key. Too strong reducing conditions will form metallic iron which then could react with sulfur to form iron sulfide which will lower the matte grade and increase the matte volume, or the metallic iron will form iron arsenide which changes the nature of the speiss. The following effects of obtaining a more reducing atmosphere can be noted:

- iron is reduced from slag and lowers the matte grade (copper content decreases),
- iron concentration in speiss also increases,
- copper concentration in speiss increases while content in matte decreases,
- slight increase of copper concentration in lead phase which will affect de-drossing within lead refinery,
- lead content in slag decreases and while lead concentration in speiss remains constant, the crude lead phase is increasing,
- antimony distribution is shifting more and more towards crude lead.

Arsenic is not that much affected by changing the oxygen potential and is mainly concentrated in speiss phase. Nickel shows a similar behavior due to its limited solubility in lead.

A continuous effort to conduct such experiments linked with the permanent improvement of databases will allow to deepen the understanding of how this kind of process can be adopted to changing feed mix compositions while keeping the first-pass metal recoveries high. Additionally, this will contribute to an optimized circularity due to minimized amount of intermediates.

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