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**SCHOOL OF MINES**

**DEPARTMENT OF METALLURGY AND MINERAL PROCESSING**

**LUSAKA**

**THE EFFECT OF ACID SOLUBLE COPPER CONCENTRATES ON  
THE OPERATIONS OF THE FLASH SMELTING AND SLAG  
CLEANING FURNACES AT NCHANGA SMELTER OF KONKOLA  
COPPER MINES. PLC.**

**BY**

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*A dissertation submitted to the University of Zambia in partial fulfilment of the requirements for the award of the Degree of Master of Mineral Science in Metallurgy and Mineral Processing*

**APRIL 2017**

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## **ABSTRACT**

*Konkola Copper Mines' (KCM) Nchanga smelter utilises a modern technology of direct to blister flash smelting process designed by Outotec, Finland. Slags from the direct to blister flash smelting unit are carbothermically reduced through a two stage electric slag cleaning furnaces (ESCF) to produce blister copper of 98.25% Cu and a cobalt recoverable slag containing 3 – 5% Cu and 0.78% Co which is processed in the cobalt recovery furnace (CRF). The smelting units are designed to smelt concentrates containing a maximum of 2.5% ASCu, however operationally the ASCu content in concentrates has gone as high as 5%. The behaviour of ASCu in the flash smelting furnace (FSF) and the subsequent slag cleaning furnace (SCF) operations has not been fully established. Therefore, the aim of the research was to assess the effects of ASCu on the FSF and SCF operating efficiencies.*

*Material balance calculations for the smelting operations were done based on the actual plant data collected for a period of 8 months when the level of ASCu was greater than 1% in feed sulphide concentrates and for another 8 months period when the level of ASCu was less than 1%. The distributions of Cu, Co and Fe in the slag and blister phases were analysed based on the material balances. The degree of oxidation was assessed and compared for the two periods by analysing the sulphur levels in the blister products. The consumption of metallurgical coke in the reduction furnaces was also analysed based on the calculations of coke specific consumption per tonne of copper produced.*

*At less than 1% ASCu in concentrate blends, Cu-in-FSF slag was found to have a negligible dependence on ASCu with the values of Cu-in-FSF slag fluctuating below 19.5%. Cu-in-FSF slag was ranging from 19.6% to 21.2% for ASCu in feed concentrates in the range 1.5% to 4.8%. The degree of oxidation was found to be very sensitive to variations in concentrate blends. Increases in ASCu lower the degree of oxidation which was evidenced by high values of S in blister at 2200 ppm with a subsequent deportment of Co to blister at 170 ppm against a set target of 69 ppm. High Cu losses to FSF slag has a tendency of reducing the loss of cobalt to blister by Cu-Co co-reduction, but however negatively impacts on coke consumption. Per tonne of Cu produced, the electric slag cleaning furnaces' coke consumption increases with increasing %Cu-in-FSF slag feed. Losses of Co in both FSF and SCF operations lowered the total cobalt recovery in the smelting operations. Further work on thermodynamically assessing the effects of ASCu on the flash and slag cleaning operations was recommended.*

## **CERTIFICATE OF APPROVAL**

This dissertation of Tichaona Mukono has been approved as a partial fulfilment of the requirements for the award of the Degree of Master of Mineral Science in Metallurgy and Mineral processing at the University of Zambia.

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## **DEFINITION OF TERMS**

ASCu	Acid Soluble Copper
BP	Blend Plan
CRF	Cobalt Recovery Furnace
DBFS	Direct Blister Flash Smelting
ESCF	Electric Slag Cleaning Furnace
FSF	Flash Smelting Furnace
KCM	Konkola Copper Mines
mt	metric tonnes
RMHS	Raw Materials Handling Section
SCF	Slag Cleaning Furnace
TCu	Total Copper
UNZA	University of Zambia

# 1 INTRODUCTION

## 1.1 Background of Study

In conventional copper extraction, the copper sulphide minerals from which about 80% of the world's copper originates are insoluble in aqueous solutions hence much of the copper extraction is through the pyrometallurgical route (Davenport *et al.*, 2002). In this pyrometallurgical route, the copper sulphide mineral particles are separated from the gangue minerals by froth flotation to obtain a copper concentrate (20 – 30% Cu) which is then melted at about 1250°C and oxidised (smelting) to produce a sulphide rich melt called matte (45-75% Cu) and an oxide rich melt called slag (1 - 2% Cu). The separation of the two melts (matte and slag) in the smelting process is enhanced by the addition of silica flux (SiO<sub>2</sub>) which makes them immiscible. The molten matte from the smelting process is further oxidised in the converting process where blister Cu (99% Cu) and slag (4 – 5% Cu) are produced (Davenport *et al.*, 2002).

Concentrates from the Zambian Copperbelt are complex with high copper, low iron, high silica contents and also contain cobalt and acid soluble copper (ASCu) which makes them challenging to process with conventional methods (Mponda *et al.*, 2010). As such Konkola Copper Mines (KCM) Nchanga smelter utilises a modern technology of Direct Blister Flash smelting process designed by Outotec, Finland. The copper sulphide and oxide mineral particles in the concentrate blend are oxidised by a concentrate burner at 75% oxygen enrichment to produce blister containing up to 99.4% Cu which is tapped to anode furnaces for refining. As a result of the highly oxidising environment in the Flash Smelting Furnace (FSF), recovery of sulphur to the gas phase is high, but the slag contains high amount of Cu (18 – 21%). Energy and dust recovery is achieved through channelling the gases in the boiler and electrostatic precipitator (ESP), respectively (Mponda *et al.*, 2010).

Carbothermic reduction of the slags is done through two stage electric slag cleaning furnaces (ESCF) to produce blister copper of 98.25% Cu and slag containing 3 - 5% Cu, 0.78% Co. (Czemecki *et al.*, 2009). The slag from the ESCF is transferred to the cobalt recovery furnace (CRF) which offers a more reducing environment for the recovery of Cu, Co and Fe, to produce a cobalt alloy and a slag containing as low as 0.45% Cu and 0.2% Co (Czemecki *et al.*, 2009).

The smelting units are designed to smelt concentrates containing 2.5% ASCu, however operationally the ASCu content in concentrates has gone up as high as 5%. The behaviour of ASCu in the FSF and SCF operations has not been fully established. Therefore, the aim of the research is to investigate the effect of ASCu in FSF and SCF operations with variations in the ASCu content of the concentrate blend.

## **1.2 Statement of the Problem**

KCM's Nchanga smelter treats sulphide concentrates in the range 23 – 40% TCu. According to the smelter design, the ASCu content in the concentrates should be maintained at below 2.5% Cu and this renders the concentrates selection criterion limited to highly sulphidic concentrates. However, operationally the ASCu content has gone up as high as 4.8% Cu without any operational challenges. This might be an indicator that Nchanga smelter has the potential of treating more ASCu concentrates, or the smelter campaign life is being affected and this has not been realised yet. The behaviour of ASCu in FSF and SCF operations has not been fully established. Consequently, this study was proposed to investigate the effect of ASCu on the FSF and SCF as well as the extent over which ASCu can be utilised.

## **1.3 Aim of Study**

The aim of this research study is to investigate the effect of ASCu on the FSF and SCF operating efficiencies using secondary data.

## **1.4 Study Objectives**

The objectives of the study are:

- ✓ To establish the distribution of Cu in the blister copper and slag phases of the FSF and SCF operations.
- ✓ To establish the effects ASCu has on FSF operations as well as the downstream operations i.e. SCF and CRF operations.
- ✓ To assess the implications of ASCu on Co partitioning in FSF and SCF as well as the overall recovery of Co in the CRF.

## **1.5 Research Questions**

The following research questions were formulated:

1. What is the distribution of Cu between blister metal and slag, during direct-to-copper flash smelting and slag cleaning operations?

2. Does ASCu has an effect on loss of Cu to the slag phase in FSF operations?
3. How is the overall Co recovery affected by operational effects of ASCu in FSF and CRF?

### **1.6 Significance of the Study**

The study will improve the understanding of the thermodynamic behaviour of ASCu as well as its effect on FSF and SCF operations, and improve the management of blister Cu. According to design, the FSF can smelt at a concentrate feed-rate of 110 mt/hr, apparently the current feed-rate is around 77.5 mt/hr, which translate to 70% furnace utilisation. Therefore, the study can increase the raw material base. The company will benefit from the following:

- ✓ An understanding of the operational challenges associated with the smelting of ASCu in the feed concentrate.
- ✓ Increased productivity.

### **1.7 Layout**

This dissertation focuses on the effect that acid soluble copper has on the direct-to-blister flash smelting and slag cleaning operations.

In Chapter 2, provides a literature review on copper flash smelting and slag cleaning. Concentrate feed quality, slag chemistry and intrinsic control parameters of the FSF and SCF are discussed. This information provides an understanding of the smelting of copper concentrates in Outotec's direct-to-copper flash smelting technology.

Chapter 3 discusses the materials and methods employed.

In Chapter 4, secondary data was analysed and the effects of ASCu discussed and validated with literature.

Finally, in Chapter 5 conclusions are drawn with recommendations for further study given.

## 2 LITERATURE REVIEW

### 2.1 Introduction

Metallurgical reactions take place either at high temperature or in aqueous solutions. More rapid reaction rates do occur at high temperatures and as such, large scale metal production is mostly achieved through high temperature processes (Seetharaman, 2005). Henceforth, this research is focused on the pyrometallurgical route of copper smelting.

### 2.2 Conventional Pyrometallurgical Copper Production

About 80% of the world's copper is produced by pyrometallurgy (Davenport *et al.*, 2002). The general flowsheet of a conventional pyrometallurgical extraction of copper is shown in Figure 2.1 below.

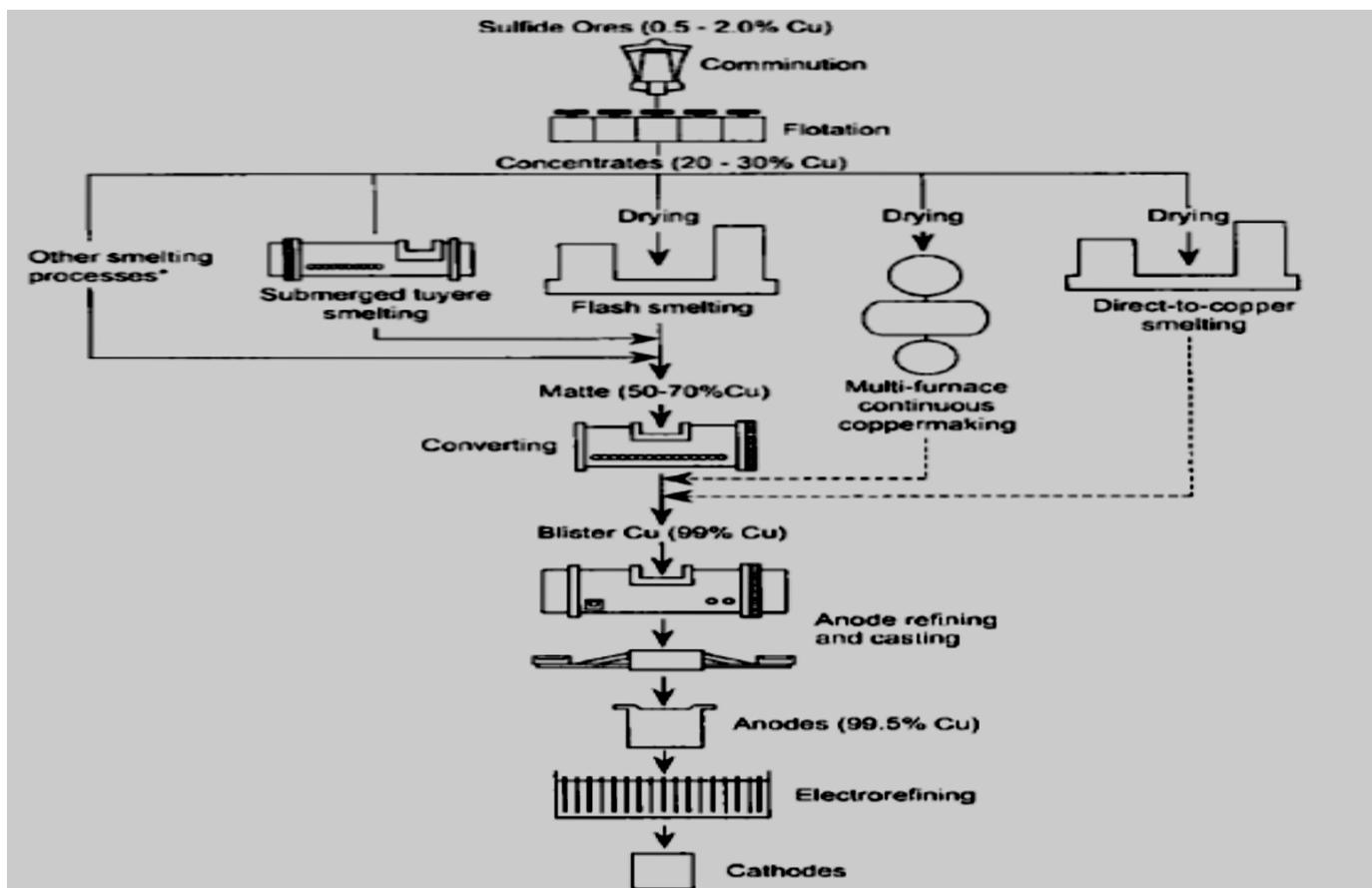


Figure 2.1: General flowsheet of a conventional pyrometallurgy process (Davenport *et al.*, 2002)

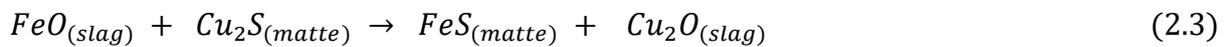
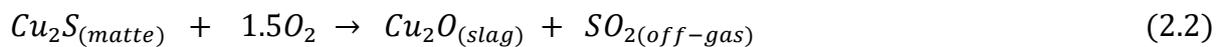
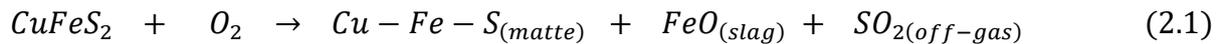
The conventional pyrometallurgy of copper is made up of the following steps:

- Matte smelting
- Converting

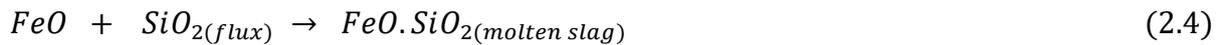
- Fire refining and Anode casting

### 2.2.1 Matte smelting

Matte smelting consists of melting concentrates or partially roasted concentrates at 1150°C – 1250°C to produce two separable (immiscible) liquid phases: slag (oxide) and copper rich matte (sulphide). This is done by reacting sulphide minerals with oxygen. The oxygen is almost always fed as oxygen enriched air or pure commercial oxygen. The matte smelting reactions take the form of the equations below (Davenport *et al.*, 2002):



Fluxing is also achieved in matte smelting by addition of silica flux according to the following equation:



The primary goal of fluxing is to promote matte-slag immiscibility (Zivkovic *et al.*, 2009). The matte smelting products are:

- 1) Molten sulphide matte (45 – 75% Cu) containing most of the copper in the concentrate
- 2) Molten oxide slag as free of Cu as possible
- 3) SO<sub>2</sub> bearing off-gas (10 to 60% SO<sub>2</sub>)

Matte smelting is done in flash furnaces, blast furnaces, reverberatory furnaces and electric arc furnaces (Davenport *et al.*, 2002).

### 2.2.2 Converting

Converting is the oxidation of molten Cu-Fe-S matte to form blister copper (99% Cu). It involves oxidising Fe and S from the matte with oxygen enriched air. Converting is commonly done in a Pierce-Smith (PS) converter. Molten matte tapped from the matte smelting furnace is transferred to the PS converter for the production of blister copper. Air is blown into the matte through tuyeres and oxygen reacts with sulphur, iron, and copper. The sulphur from the metal sulphides provides the energy to complete the conversion of matte to

blister copper i.e. the reaction is exothermic. The following diagram in Figure 2.2 depicts the PS converter (Zun-qiu, 2003).

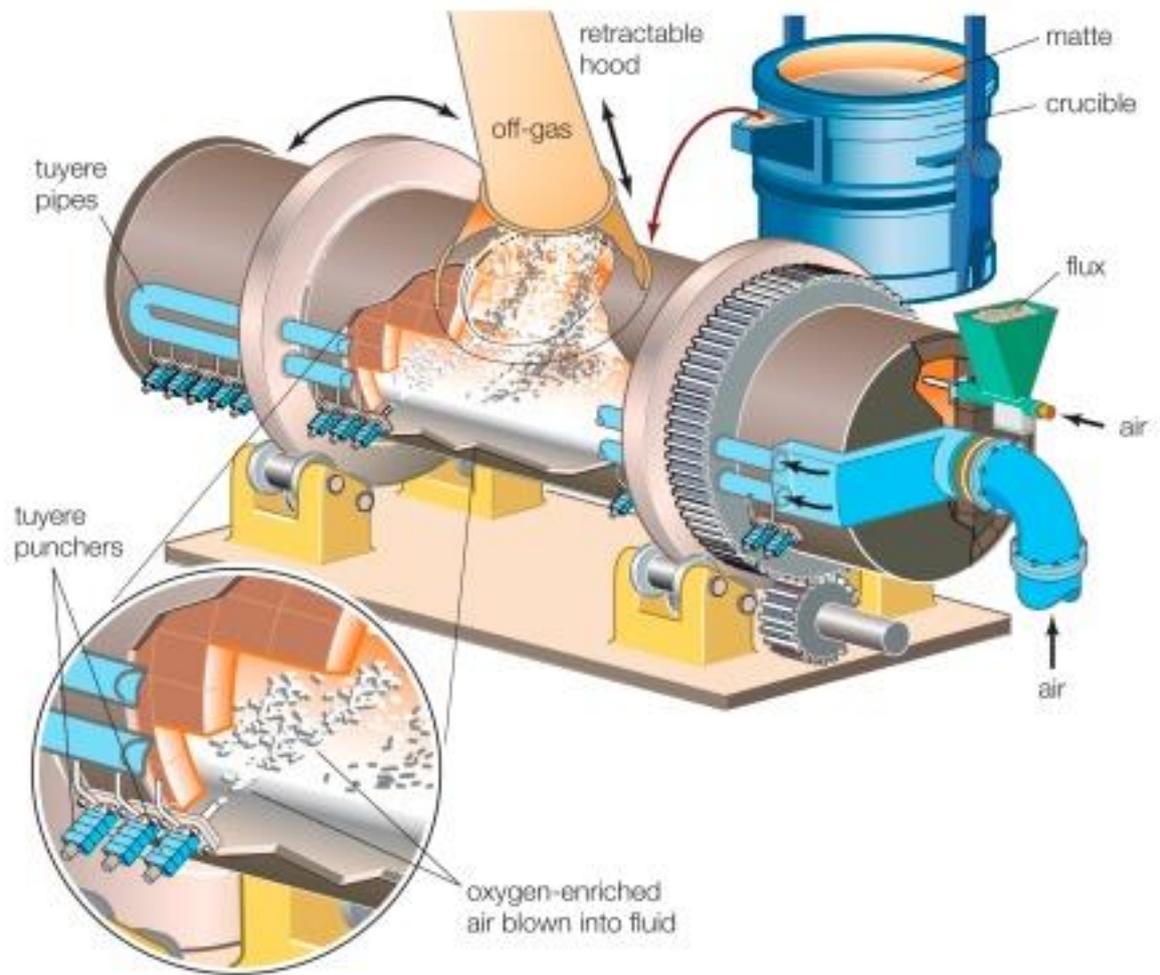


Figure 2.2: Pierce Smith Converter (Zun-qiu, 2003)

The overall converting process is represented by the schematic equations below and the process takes place in two sequential stages (Davenport *et al.*, 2002):

- a) The slag forming stage:



The principal product of the slag forming stage is impure molten  $Cu_2S$  (white metal).

- b) The blister copper forming stage



The copper making stage does not occur until the matte contains less than 1% Fe so that Fe can be removed from the converter (as slag) before copper production begins (Ashman *et al.*, 2013). Sulphur content in the blister copper is around 0.02% (Ashman *et al.*, 2013).

### 2.2.3 Fire Refining and Anode casting

Blister copper from converting is subsequently fire-refined before being cast into anodes. This is done in anode furnaces with the objective of eliminating most of the sulphur and oxygen contained in the blister Cu. The process of fire-refining is made up of two stages:

- a) The oxidation stage: In this stage the bath is oxidised using oxygen to remove sulphur as  $SO_2$ . The sulphur is removed by the reaction of the blister Cu with an oxidising flame above the bath according to the following equation (Davenport *et al.*, 2002):



Sulphur is reduced to a level of 0.001% to 0.003% S in the Cu

- b) The reduction stage: The main purpose of the reduction stage is to remove the oxygen which may have been dissolved in the bath during oxidation. Reduction is achieved by floating wooden poles on the molten copper in a process known as poling or alternatively diesel can be used as a reductant. The oxygen is reduced from about 0.6% down to 0.05% (Davenport *et al.*, 2002). The following schematic equations depict the reduction process:



Finally the impure copper anodes are electrolytically refined to produce 99.99% Cu. Electro-refining produces copper essentially free of harmful impurities and also separates valuable impurities e.g Au and Ag from the Cu for recovery as by-products (Davenport *et al.*, 2002).

## 2.3 Flash Smelting

Two processes for flash smelting were developed in the 1940s. Inco developed the oxygen flash smelting in Canada and Outokumpu developed the air flash smelting in Finland. The Outokumpu process uses preheated air, or preheated or ambient oxygen enriched air. This process is not autogenous unless the ingoing air is extensively enriched with oxygen. To make up the thermal deficit in the Outokumpu process, hydrocarbon fuel is used. The early 1970s saw an increased concern for protecting the environment and for minimizing

energy consumption. Flash smelting is advantageous in both aspects and hence it emerged as a major smelting method (Davenport *et al.*, 2002).

Flash smelting consist of injecting fine, dry sulphide concentrates with gaseous oxygen into a hot furnace. Concentrate reacts with oxygen exothermically under these conditions to produce (Davenport *et al.*, 2010):

- 1) A liquid sulphide matte phase
- 2) A liquid oxide 'slag' phase
- 3) A gas phase with a high concentration of  $SO_2$

The matte contains most of the primary metal values (Cu, Co, Ni) while the slag is dilute in these. The concentration of primary metal values into the matte phase is the main objective of the flash smelting process. Primary smelting in flash smelting occurs in the reaction shaft as shown in Figure 2.3 (Taskinen *et al.*, 2003):

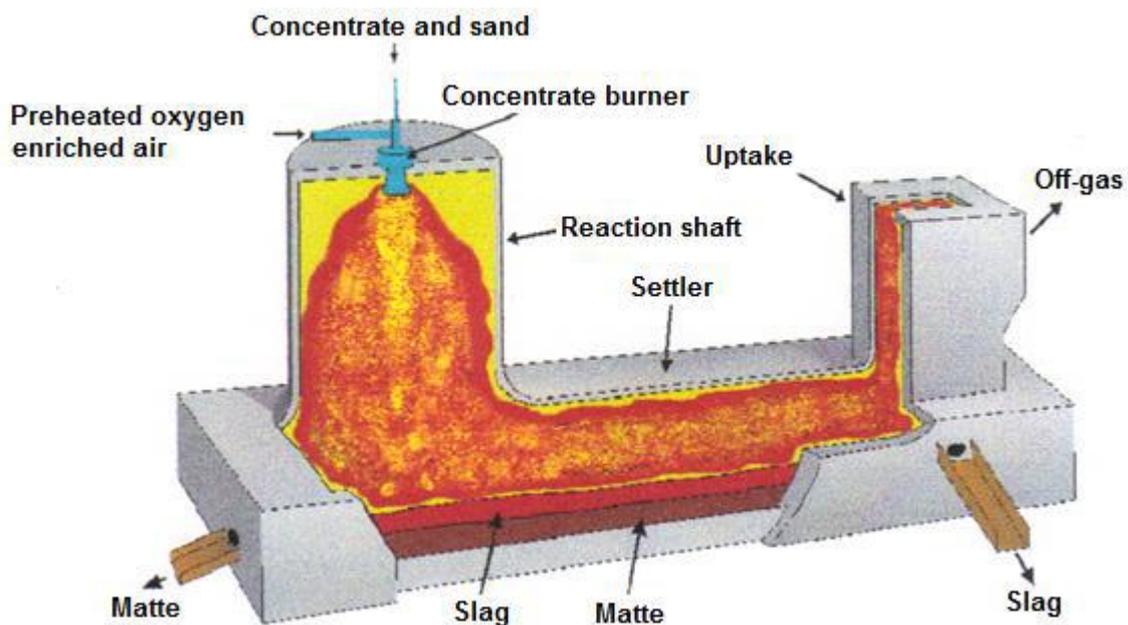


Figure 2.3: A cut-way diagram of flash smelting showing that primary smelting occurs in the reaction shaft (Taskinen *et al.*, 2003)

### 2.3.1 Raw Materials

Copper flash smelting principal raw materials are (Davenport *et al.*, 2002):

- i) Dry sulphide copper concentrates
- ii) Flux ( $SiO_2$ )
- iii) Gaseous oxygen

Additional hydrocarbon fuel may also be necessary to provide supplementary heat energy.

### 2.3.1.1 Copper concentrate

Approximately 90% of the copper in the earth's crust occurs as sulphide minerals of which the most common is chalcopyrite ( $CuFeS_2$ ) (Davenport *et al.*, 2010). Chalcopyrite is easily flash smelted since the oxidation of the iron and sulphur is exothermic. Chalcocite ( $Cu_2S$ ) and bornite ( $Cu_5FeS_4$ ) which are a characteristic of the Zambian Copperbelt, also occur along with chalcopyrite (Partelpoeg *et al.*, 2010).

Copper sulphide ores are virtually always concentrated by froth flotation with typical concentrate grades of about 20 - 30% Cu. The ore particle size is approximately 50 $\mu$ m during the concentration process and is also very suitable for rapid oxidation during flash smelting. Concentrates are dried prior to flash smelting to ensure good dispersion in the oxidant as they enter the furnace. This mixing is necessary for the reactions to occur quickly and efficiently (Partelpoeg *et al.*, 2010).

### 2.3.1.2 Silica Flux

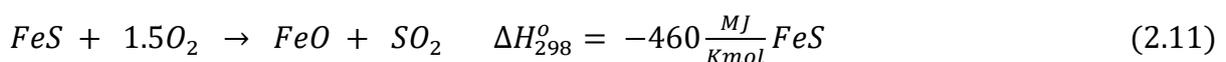
Silica flux (typically 90%  $SiO_2$ , 10%  $Al_2O_3$ ) is usually mixed with the concentrate prior to drying and smelting. Its purpose is to combine with the gangue in the concentrate and the iron oxide produced during combustion of the concentrate to form a liquid phase which is immiscible with the sulphide matte phase (Davenport *et al.*, 2010).

### 2.3.1.3 Source of gaseous oxygen

The gaseous oxygen with which concentrates react in a flash furnace may be in the form of air, air mixed with commercially pure oxygen, or commercially pure oxygen itself (Davenport *et al.*, 2010).

## 2.3.2 Flash smelting reactions and products

The principal reactions which occur during smelting of chalcopyrite concentrate in a flash furnace can be represented as follows:



The reactions are highly exothermic and as such provide much or all of the thermal energy required to heat, melt and superheat the smelting furnace products.  $Cu_2S$  and  $FeS$  are completely miscible above 1375K, forming a liquid sulphide matte phase which settles in the hearth flash furnace.  $Cu_2S$  does not oxidise appreciably in flash furnace because  $FeS$  oxidises preferentially.  $Cu_2O$  which does form is reduced by  $FeS$  back to  $Cu_2S$ , except for a small fraction which remains as a component of the total copper losses to the slag.  $Cu_2O$  is reduced by  $FeS$  according to the following equation (Davenport *et al.*, 2010):



$FeO$  formed in the flash furnace is fluxed with silica according to the following reaction:



The product is a liquid slag phase which is immiscible with the matte and which, being less dense, floats on top of the matte. Flash furnace off-gas consist of  $SO_2$  produced by the matte smelting reactions and  $N_2$  from the oxidant. If supplementary fuel is burnt, the combustion products of the fuel ( $CO_2$  and  $H_2O$ ) are also constituents of the off-gas. Off-gas  $SO_2$  concentration is determined by the extent of oxygen enrichment and by the amount of the hydrocarbon fuel. In industrial flash furnace  $SO_2$  concentration range from 15 – 80%, considerably greater than those produced by reverberatory furnace (0.5 – 3%  $SO_2$ ) and electric smelting furnace (4 – 8%  $SO_2$ ) (Davenport *et al.*, 2002).

### 2.3.3 Advantages and Disadvantages of Flash smelting

The principal advantages of flash smelting processes are:

- a) They make considerable use of the energy which is available from oxidising the sulphide minerals, and hence their fuel costs are low;
- b) Their waste gases are rich in  $SO_2$  which is efficiently removed as liquid  $SO_2$  or sulphuric acid after due processing;
- c) Their production rates are high due to the rapid rates at which the mineral particles are heated while their surfaces are being oxidised.

The principal disadvantage of the flash smelting process is that the copper content of their slags tends to be high (INCO 0.7% Cu; Outokumpu 1% Cu). Therefore, the high Cu losses to the slag phase renders flash smelting not able to efficiently recover copper from subsequent converter slags (Davenport *et al.*, 2010).

## 2.4 Direct to Blister Flash Smelting

Conventional pyrometallurgical copper making from sulphide concentrates entails two major steps which are smelting and converting. Smelting and converting are essentially, part of the same chemical process of oxidation of Fe and S from a Cu-Fe-S phase. A continuous direct to copper smelting process has been sought by metallurgical engineers in order to combine smelting and converting. As of 2011, this has been achieved in three flash furnace smelters:

- Chingola, Zambia (Taskinen & Kojo, 2009)
- Glogow II, Poland (Byszynski *et al.*, 2010)
- Olympic Dam, Australia (Ranasinghe *et al.*, 2010)

### 2.4.1 Advantages and Disadvantages

The principal advantages of combining smelting and converting are:

- a) Minimization of energy consumption;
- b) Isolation of  $SO_2$  emission to a single continuous,  $SO_2$ -rich gas stream, ideal for capturing sulphur for sulphuric acid production;
- c) Minimization of capital and operating costs

The current disadvantages of the process are that:

- a) About 25% of the copper entering a direct-to-copper smelting furnace ends up dissolved in slag (compared to < 10% in traditional Pierce-Smith converting)
- b) The cost of recovering this lost copper is high and as such will probably restrict future expansion of direct-to-copper smelting to low-Fe chalcocite and bornite concentrates rather than high-Fe chalcopyrite concentrates; smelting of low-Fe concentrates generate less slag and therefore less copper loss (Czemecki *et al.*, 2009).

Figure 2.4 is a typical simplified direct to copper flowsheet at Olympic Dam:

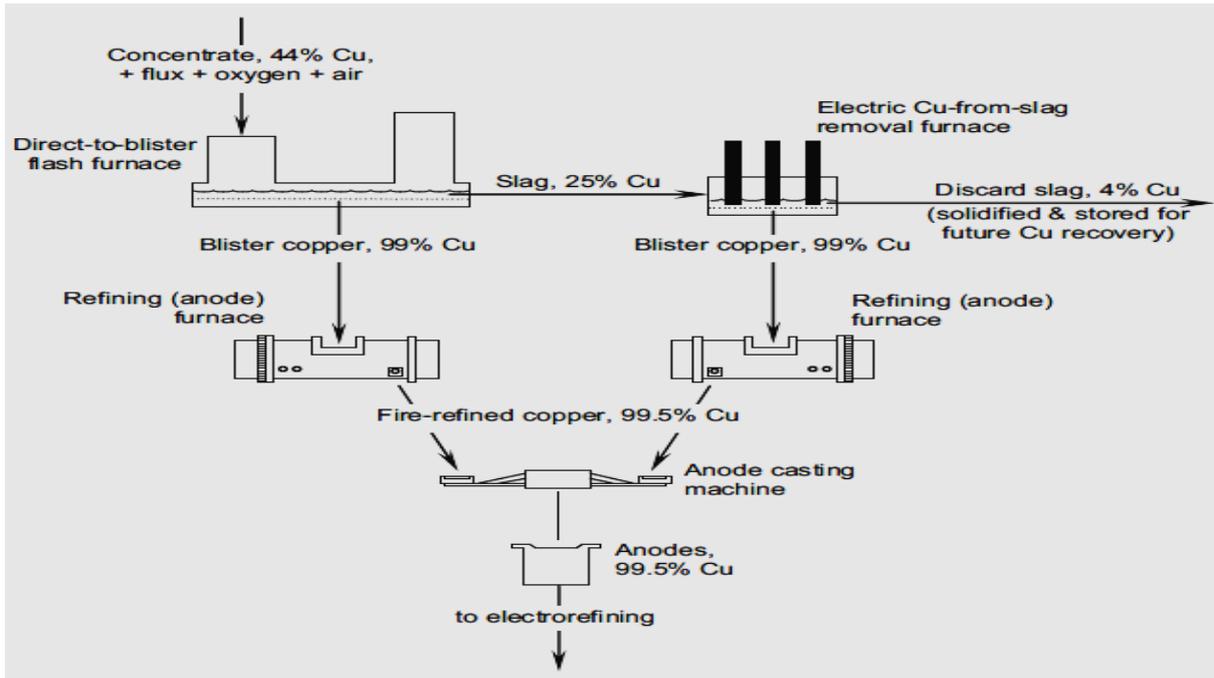


Figure 2.4: Simplified Olympic Dam direct-to-copper smelter flowsheet (Ranasinghe et al., 2010)

Ideally, the principal inputs to the direct-to-copper smelting process are concentrate, oxygen, air, flux and recyclables. The principal outputs are molten copper, low-Cu slag and high- $SO_2$  off-gas. For the ideal process, the Cu is low in impurities, the slag is discarded without further Cu-recovery, and off-gas is strong in  $SO_2$  for sulphuric acid manufacture. Also little or no fossil fuel is required. Figure 2.5 is a schematic representation of the ideal direct-to-copper smelting process (Partelpoeg et al., 2010).

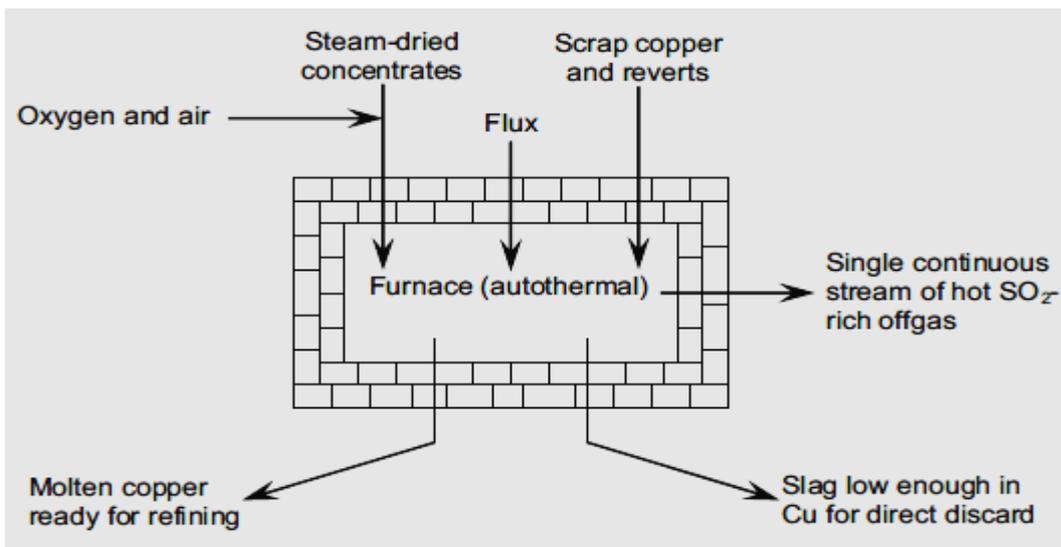


Figure 2.5: Ideal single-furnace (Direct-to-copper) copper making process (Partelpoeg et al., 2010)

## 2.4.2 Industrial Single furnace direct-to-copper smelting

The direct to copper process is continuous and auto-thermal. With highly oxygen-enriched (low Nitrogen gas) blast, there is excess reaction heat to melt all the Cu-bearing recycled materials from the smelter and adjacent refinery, including scrap anodes. Tables 2.1-3 describe the concentrates currently being smelted in established direct-to-copper furnaces.

Table 2.1: Elements and Equivalent Minerals in Chingola Direct-to-Copper flash furnace concentrate feed (Syamujulu, 2007)

Element	Cu	Fe	S	SiO <sub>2</sub>	Other
Mass (%)	39% mainly in chalcocite, bornite & chalcopyrite	8% mainly in bornite & chalcopyrite (minor in pyrite)	19% mainly in chalcocite, bornite & chalcopyrite	18% mainly in feldspar and clay	10% Al <sub>2</sub> O <sub>3</sub> (mainly in clay) 2% CaO 2% MgO

Table 2.2: Elements and Equivalent Minerals in Olympic Dam Direct-to-Copper flash furnace concentrate feed (Solnordal et al., 2006)

Element	Cu	Fe	S	SiO <sub>2</sub>		
Mass (%)	44	20	25	5		
Minerals	Bornite (Cu <sub>5</sub> FeS <sub>4</sub> )	Digenite (Cu <sub>1.8</sub> S)	Chalcopyrite (CuFeS <sub>2</sub> )	Quartz (SiO <sub>2</sub> )	Pyrite (FeS <sub>2</sub> )	Hematite (Fe <sub>2</sub> O <sub>3</sub> )
Mass (%)	28 – 45	25 - 35	11 – 27	2 – 6	0.2 – 2	8 – 12

Table 2.3: Elements and Equivalent Minerals in Glogow Direct-to-Copper flash furnace concentrate feed (Dobrzanski & Kozminski, 2003)

Element	Cu	Fe	S	'Free' carbon	Pb	As	Other
Mass (%)	17 – 31	2 -7	8 – 11	5 - 8	1.5 - 3	0.05 - 4	42 - 50
Minerals	In chalcocite (Cu <sub>2</sub> S) and bornite (Cu <sub>5</sub> FeS <sub>4</sub> )	In bornite (Cu <sub>5</sub> FeS <sub>4</sub> ) And hematite (Fe <sub>2</sub> O <sub>3</sub> )	Mainly in chalcocite and bornite	Carbon	In galena, (PbS)	In arsenopyrite, (FeAsS <sub>2</sub> ), enargite, (Cu <sub>3</sub> AsS <sub>4</sub> ), tennantite	20% SiO <sub>2</sub> , 6% Al <sub>2</sub> O <sub>3</sub> , 6% CaO, 4% MgO, K <sub>2</sub> O, Na <sub>2</sub> O

Outotec (formerly Outokumpu) flash smelting is the only single furnace direct-to-copper process, producing copper in one stage currently. The products of direct-to-copper flash smelting are impure molten copper (99% Cu, 1300 °C), molten slag (12 – 18% Cu, 1310 °C) and off-gas (16 – 41 vol. %  $SO_2$ , 1250 – 1400 °C). Table 2.4 shows the products of direct to copper smelting.

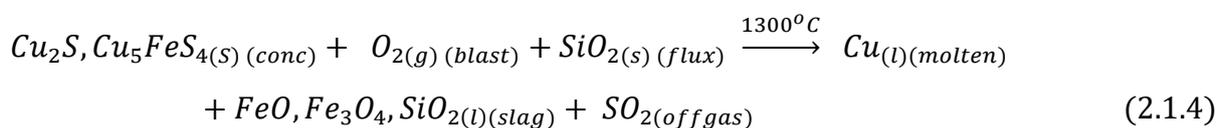
Table 2.4: Products from Direct-to-Copper flash smelting (Davenport *et al.*, 2010)

Smelter								
Element/compound	Cu	Fe	$SiO_2$	CaO	MgO	$Al_2O_3$	$K_2O$	$Na_2O$
	Mass (%)							
Olympic Dam, Australia	23 - 28	33	18	0	0	3.5		
Glogow, Poland	12 - 15	6	31	14	6	9	Yes	Yes
Chingola, Zambia	17 - 20	17 - 29	28 - 32	5	3 - 7	5 - 7		

As with conventional matte flash smelting, the temperature in the smelting furnace is controlled by adjusting (a) the degree of oxygen enrichment of the blast (which changes the amount of  $N_2$  coolant entering the furnace) and (b) the rate at which fossil fuel is burnt in the furnace. The  $O_2$  content of industrial direct-to-copper flash furnace blast is 69 – 95 vol. %  $O_2$ , depending on the concentrate composition. Considerable fossil fuel is burnt in the reaction shaft and in settler burners (Davenport *et al.*, 2010).

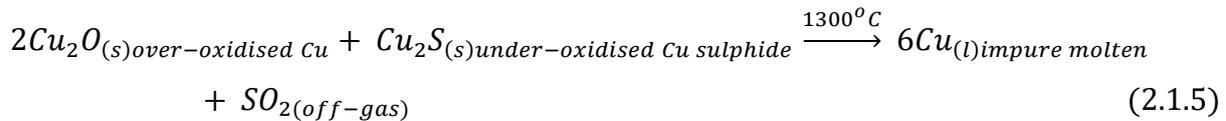
### 2.4.3 Direct to Blister Flash Smelting process Chemistry

The following schematic (unbalanced) reaction describes how the direct-to-copper smelting process takes place (Davenport *et al.*, 2010):

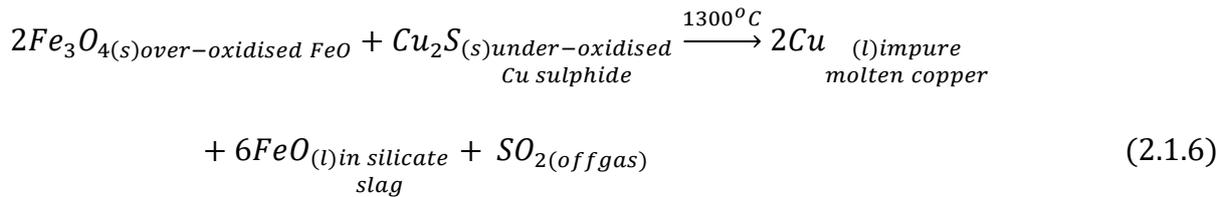


Oxygen supplied is just enough to produce metallic copper rather than  $Cu_2S$  or  $Cu_2O$ . However, operationally, the flash furnace reaction shaft product is a mixture of over-oxidised (oxide) and under-oxidised (sulphide) materials. Mineral particle entities may be over-oxidised on the outside and under-oxidised on the inside. The over- and under-oxidised

components react to give metallic copper, as shown in the reactions below (Davenport *et al.*, 2010):



And



The overall extent of reaction (2.1.4) is controlled by

- (a) Monitoring the Cu content of the product slag and the S content of the product copper
- (b) Adjusting the ratio of oxygen in the blast to concentrate fed to the furnace.

This control philosophy is based on the measured Cu-in-slag and S-in-copper values. An increasing Cu content in the slag is reversed by decreasing the  $O_2$ /concentrate ratio and vice versa. Industrially, the slag copper content is kept between 12 and 28% (Davenport *et al.*, 2010).

#### 2.4.4 Industrial control philosophy of direct-to-copper smelting

Products composition of industrial direct-to-copper flash smelting furnaces are basically controlled by adjusting the ratios of oxygen in the blast to concentrate feed rate and flux/concentrate feed rate. Temperatures of the products are controlled by adjusting the blast oxygen-enrichment level and the rate at which fossil fuel is burnt in the furnace.  $O_2$ /concentrate ratios in industrial direct-to-copper furnaces are kept high enough to avoid forming a  $Cu_2S$  layer. A molten  $Cu_2S$  layer, once built up between the molten copper and molten slag layer, has the potential to react with slag by reactions such as (2.1.5) and (2.1.6), which can produce  $SO_2$  beneath the slag layer. This  $SO_2$  causes slag foaming to occur. Thus,  $O_2$ /concentrate ratios are critically controlled to avoid the possibility of foaming slag out of the top of the furnace (Hunt *et al.*, 1999).

Subsequent increase in the  $O_2$ /concentrate ratio in order to shrink or remove an existing  $Cu_2S$  layer favors slag foaming. This is so, because it results in a highly oxidised slag, full of dissolved  $Fe_3O_4$  and  $Cu_2O$ , which has great potential for producing  $SO_2$  beneath the slag

layer. The foaming problem is avoided by ensuring that  $O_2$ /concentrate ratio is always at or above its set point. This may lead to high Cu-in-slag levels but it avoids the potentially serious operational problems emanating from foaming (Davenport *et al.*, 2010).

The control philosophy of avoiding  $Cu_2S$  is also referred to as the no-matte-layer control strategy. An unfortunate side-effect of the no-matte-layer strategy is a high Cu content in the slag, mainly as dissolved  $Cu_2O$ . It arises because there is no permanent layer of  $Cu_2S$  in the furnace to reduce  $Cu_2O$  to metallic copper, by reaction (2.1.5). The copper lost to the slag phase is scavenged in a slag cleaning stage (Davenport *et al.*, 2010).

## **2.5 Nchanga Copper Smelter**

### **2.5.1 Process Concept**

Nchanga smelter has a concentrate smelting capacity of 849 000 tonnes per annum (t/a), with copper content of 311 860 tonnes Cu per annum (tpa). The smelter utilises a Direct to Blister Flash (DBF) smelting furnace where the feed mixture is directly processed to blister copper. Blister copper is transferred from the DBF via launders to anode furnace treatment. The resultant slag from the DBF is treated in an electric slag cleaning furnace (SCF) by coke reduction to lower the copper content down to 5%. Metallic copper thus formed is also laundered to the anode furnace. Final slag cleaning and cobalt recovery takes place in two parallel electric furnaces (CRF) allowing two times longer retention time compared to SCF which contributes to high cobalt and copper recovery in the CRF. Slag is treated by coke reduction to lower the copper and cobalt contents to 0.4% Cu and 0.24% Co, respectively. Some concentrate mixture is injected to the bath to increase the sulphur content of Cu-Fe-Co alloy settling to the bottom of the furnace. The alloy and the waste slag are granulated directly from the furnace. The basic flowsheet and principal material streams of the Nchanga smelter are illustrated in Figure 2.6 (Mponda *et al.*, 2010).

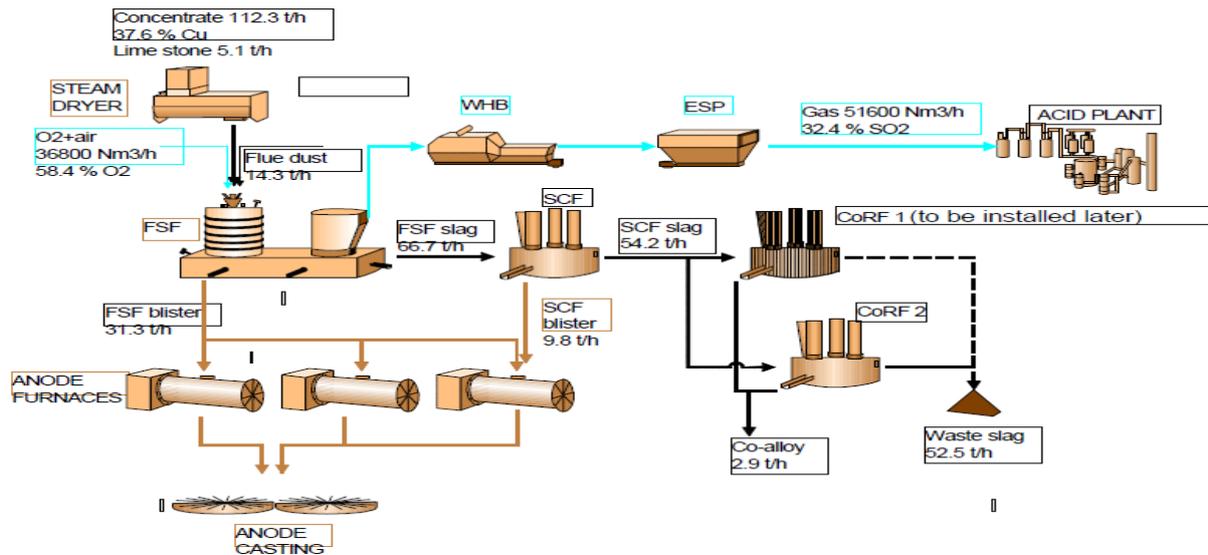


Figure 2.6: Flowsheet of the Direct-to-Blister Process at Nchanga Smelter (Mponda *et al.*, 2010)

## 2.5.2 Feed to the smelter

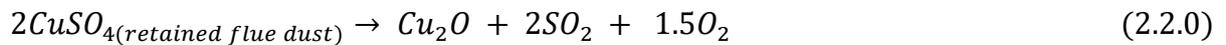
In the work undertaken by Mponda *et al* (2010) concentrate feed blend projected in the design of the KCM smelter was mainly composed of Konkola and Lumwana concentrates (> 70% of the blend). Minor components were Nchanga, Kansanshi and Chibuluma concentrates. Copper from the Kansanshi concentrates is almost entirely bound to chalcopryrite while in the other concentrates copper occurs either in chalcocite or bornite or in both minerals in varying proportions. Pyrite is the main sulphide mineral carrying iron. Non-sulphide copper minerals encountered in the concentrates are malachite, pseudomalachite, chrysocolla and cuprite. Gangue minerals are typically various types of hydrated silicates (talc, feldspar etc.) and carbonates.

Fe/SiO<sub>2</sub> ratio in the concentrate is generally low and this enables the use of calcium oxide as a fluxing agent resulting in iron-calcium-silicate slag instead of iron silicate slag. Iron-calcium-silicate slag absorbs less copper compared to iron silicate slag (Davenport *et al.*, 2002). Therefore, a high copper recovery is achieved directly to blister copper formed in the flash furnace. This reduces reduction work in the subsequent slag-cleaning steps. The blended concentrate mixture containing 10 – 15% moisture is dried before smelting in a steam drier at the temperature range of 105 - 115°C with low energy consumption to produce a dried concentrate feed containing less than 0.3% of moisture. The dried concentrate is mixed with O<sub>2</sub> enriched process air (50 – 90% O<sub>2</sub>) in the concentrate burner to form even suspension in the DBF reaction shaft. Additional fuel oil, when required, is introduced into

the reaction shaft by oxy-fuel burners or through the fuel lance located in the middle of the concentrate burner (Mponda *et al.*, 2010).

### 2.5.3 Key Reactions

The concentrate feed blend enters the hot reaction shaft environment and some components of the feed decompose according to the following decomposition reactions:



All hydroxides, carbonates and crystal water containing minerals (malachite, chrysocolla, talc etc.) identified in the concentrate mixture dissociate at high temperature prevailing in the reaction shaft. These reactions are highly endothermic in nature (Simunika, 2014). In the high temperature region of the reaction shaft, the sulphidic components of the feed mixture react exothermically with oxygen in the enriched process air through the following reactions:



The completion of these reactions depends on the degree of oxidation in the reaction shaft, which also depends on the affinity of each metal sulphide to oxygen. Zinc, Lead and Iron

sulphides are oxidised more easily than copper sulphides and their oxidation significance is negligible because their concentrations in the feed mixture are very low. The iron in the feed mixture reacts mainly according to the reaction (Simunika, 2014):



Oxidation of copper sulphides mainly occurs by the following reactions:



In the settler, excessive copper oxide is reduced by copper sulphide according to the following reaction:



The sulphur in blister copper is in equilibrium with oxygen dissolved in blister copper and gas phase according to the equations:



The more oxidising the conditions are, the less sulphur there is in the blister. Limestone is added to the FSF feed in order to control magnetite content and improve the slag fluidity. Silica in concentrate reacts with calcium oxide which originates from the decomposition of limestone as follows (Simunika, 2014):



#### **2.5.4 Cu in Slag limitation**

In direct to blister process, about 25% of the copper in feed reports to the slag phase (Taskinen and Kojo, 2009). The copper content in the slag phase is relatively low if the slag composition is essentially a Ca-Al-Mg-K-Na silicate slag, which has a relatively low solubility of copper oxide. The principal disadvantage of the direct-to-copper process is its large loss of copper in slag. It therefore, appears that direct-to-copper process is best suited to concentrates containing chalcocite ( $Cu_2S$ ) and bornite ( $Cu_5FeS_4$ ) as well as other normal chalcopyrite concentrates (Touminen and Kojo, 2005).

Chikashi (2011) studied the influence that each component of slag has on the losses of copper in slag cleaning furnace using linear regression analysis method. In the study  $Fe_3O_4$  and  $SiO_2$  were established to be the main components in the flash furnace feed and slag to be controlled to levels which will enable better control of copper in slag.

## 2.6 Electric furnace Cu-from-slag recovery

Direct-to-blister flash smelting technology shown in Figure 2.7 below is a cost-effective technology which produces slag containing up to 14 – 25% Cu (Warczok *et al.*, 2007). This makes the slag cleaning process in electric furnace inevitably important.

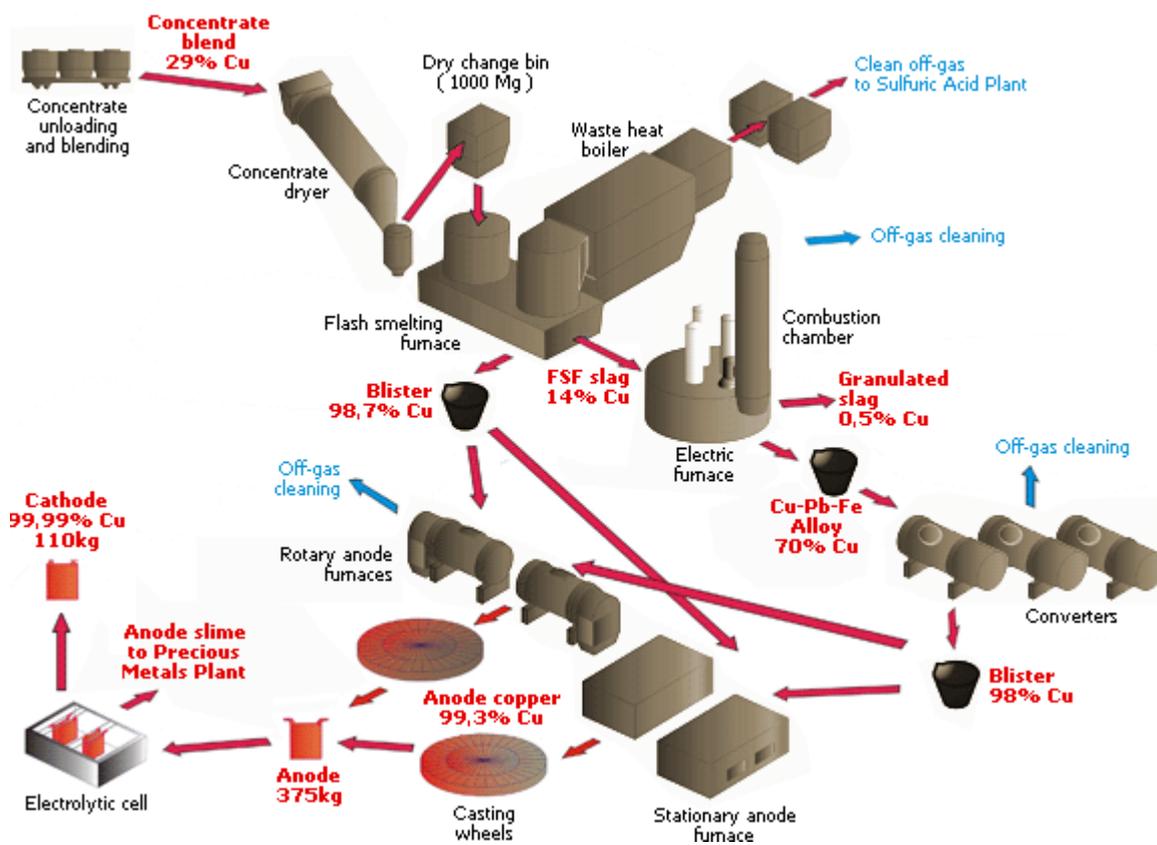


Figure 2.7: Diagram of the latest Outotec's flash smelting process showing a single step process from concentrate to an end product (Warczok *et al.*, 2007)

Recovery of copper lost to the slag phase in all direct-to-copper smelters is achieved in an electric slag-cleaning furnace. Figure 2.8 below shows a schematic diagram of electric furnace under operation with dominant reactions in the copper flash smelting slag cleaning furnace.



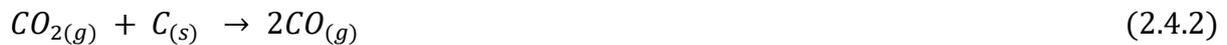
species from the original concentrate (Ranasinghe *et al.*, 2010). Henceforth, the slag is solidified and Cu recovery is done through solidification, comminution and flotation.

### 2.6.1 Carbothermic Reduction of Copper oxides

Carbothermic reduction of metal oxides refers to the reduction of metal oxides to metals by the use of carbon as the reductant. Much work has been done in describing the mechanism of carbothermic reduction of metal oxides. The oldest and most widespread is the mechanism of oxide reduction through gaseous intermediates CO and CO<sub>2</sub> in accordance with the following reactions:



Where M and MO are metal and metal oxide, respectively.



Boris (2000) studied the carbothermic reduction of copper oxides which is entirely based on the dissociative evaporation of the reactant with simultaneous condensation of low volatile product. In order to assess the potential of using copper oxide as the oxygen source in chemical looping combustion with coal, a study was undertaken by Goldstein *et al.*, (2010). The aim was to characterise the reduction reaction rates of copper oxide to metallic copper with carbon monoxide, which is a major coal partial oxidation product. In this study, two pathways for CuO to Cu were established, one cascading ( $CuO \rightarrow Cu_2O \rightarrow Cu$ ) and the other direct ( $CuO \rightarrow Cu$ ). The findings of the research indicated that chemical looping combustion of coal employing CuO as the oxygen carrier will not be limited by chemical reactions. At Nchanga smelter carbothermic reduction is employed in the Slag cleaning stage.

### 2.6.2 Slag cleaning at Nchanga

FSF slag contains copper and cobalt dissolved in its silicate matrix as oxides (Cu<sub>2</sub>O and CoO respectively) and copper also as a mechanical dispersion of blister copper in a form of small or large droplets. The FSF slag is cleaned in a two stage operation. The first step that occurs in the SCF involves the reduction of dissolved copper while the second stage that occurs in the CRF involves the removal of the residual copper and cobalt from the slag. Two reduction reactions occur in the SCF simultaneously (Simunika, 2014):

i. The dissolved magnetite (ferric iron) in the slag is converted to ferrous oxide as :



ii. The dissolved copper oxide is converted to metallic molten copper as :



As the two reactions proceed simultaneously, the lowering of copper concentration in the slag always means a simultaneous reduction of its (dissolved) magnetite concentration. One reaction does not occur without the other, and thus a significant fraction of the coke used for reduction is consumed in magnetite reduction. The formed metallic copper and mechanical blister copper dispersion settle to the bottom of furnace and form blister copper (Simunika, 2014).

In this study the acid soluble copper is part of the bulk sulphide concentrate required in flash smelting. As such, the objective of this research was to describe the behaviour of  $Cu_2O$  in the FSF. Also the implications of the acid soluble copper on the slag cleaning operations were evaluated.

## 2.7 Copper Losses and Slag Chemistry

Copper in FSF and SCF operations is present either as dissolved Cu, or entrained droplets of blister Cu. Therefore, copper losses in slag can be divided between chemical ( $Cu_2O$ ) and mechanical losses (entrained blister Cu). The percentages of these losses are dependent on the degree of oxidation or reduction, temperature and composition of the slag (which affects viscosity) (Schlesinger *et al.*, 2011).

### 2.7.1 Slag Viscosity

Mechanical Cu losses as a result of slag viscosity are mainly centred on the effect slag viscosity has on the settling rate of a metal droplet. Stokes law described by equation (2.4.5) describes effect of slag viscosity.

$$u = \frac{(\rho_{Cu} - \rho_{slag})}{18\eta_{slag}}gd^2 \quad (2.4.5)$$

Where  $u$  = settling rate,  $ms^{-1}$

$g$  = acceleration due to gravity,  $ms^{-2}$

$d$  = diameter of Cu droplet, m

$\rho_{Cu}, \rho_{slag}$  = density of copper and slag respectively,  $Kgm^{-3}$

$\eta_{slag}$  = viscosity of slag, Pa.s

The settling of copper droplets is very much dependent on the viscosity of the slag. Slag viscosity plays a vital role in the formation of copper droplets big enough to settle at the desired rates. The lower the viscosity, the better the coalescence of finer blister particles to form bigger particles, and according to Stokes equation the faster the settling (Eric, 2004). Viscosity of molten slags, which largely affect the sedimentation of inclusions in smelting processes, is sensitive to temperature and composition change. In a research by White (2006), it was established that for a common Newtonian fluid, viscosity decreases rapidly with temperature and always increases with pressure. According to Schlesinger *et al* (2011), in slag reduction processes of  $Fe^{3+}$  to  $Fe^{2+}$  viscosity of fayalitic slag decreases. Yazawa *et al* (1999), established that at constant temperature viscosity rises along with the  $SiO_2$  amount in the slag due to  $SiO_2$  forming  $SiO_4^{4-}$  chains which produce long molecules. FeO tends to reduce viscosity of the slag (Schlesinger *et al.*, 2011). Addition of CaO splits  $SiO_2$  network and thereby lowers viscosity (Yazawa *et al.*, 1999).

### **2.7.2 Effects of $Fe_3O_4$ content on control of copper in slag**

Iron in feed concentrate is oxidised to magnetite ( $Fe_3O_4$ ) in flash smelting furnace operation. The extent of oxidation as well as the amount of iron in the concentrate greatly influence the amount of  $Fe_3O_4$  in FSF slag. El-Rassi and Utigard (2000) established that losses of valuable metals (Cu and Co) to slag increase with increasing magnetite in the slag.  $Fe_3O_4$  increases the viscosity of the slag and the entrainment (mechanical losses) of molten copper droplets in the slag phase (Zivkovic *et al.*, 2009). According to Stokes law (equation 2.4.5), this will result in slow settling of molten copper droplets.  $Fe_3O_4$  also causes the formation of a false bottom between the slag and blister Cu phases. The intermediate phase (i.e false bottom) layer which is 50 to 200 mm thick insulates energy transfer and Cu droplets to the blister phase. Temperature of blister Cu in the SCF under such conditions drop below  $1130^\circ C$ , making transfer of blister to the anode furnaces difficult, because of poor flow and the metal cools easily (Chikashi, 2011). Chikashi (2011) demonstrated that at low blister tapping temperatures, the removal of solidified Cu from blister launders and the repair of blister launders become more frequent and also increases the amount of scrap copper generation that has to be re-smelted in the anode furnace, and as such the inevitable outcome is an increase in the direct processing costs.

### 2.7.3 The influence of Silica on control of copper in slag

Silica content in the slag has an impact on the viscosity of the slag (Moskalyk and Alfantazi, 2003). An increase in silica increases the amount of copper in SCF slag because of silica saturation at  $Fe/SiO_2$  ratios less than 1, resulting in high slag viscosity (Taskinen, 2009). High silica slag has got a glassy nature and as such its porosity to gases decreases, which adversely affects the reduction rates at the slag/gas interface in the SCF and also results in slag foaming in FSF operations (El-Rassi and Utigard, 2000).

### 2.7.4 The influence of Alumina on control of copper in slag

Alumina forms high-melting point compounds with  $Fe_xO_y$  and  $SiO_2$ , which are solid at copper-smelting temperatures (Taskinen, 2009). In a study using linear regression analysis of the influence that each component has on the losses of copper in slag cleaning furnace done by Chikashi (2011), it was shown that an increase of alumina in the calcium silicate slag enlarges the spinel ( $Fe_3O_4$ ) saturation area and increases mechanical losses of Cu as shown in Figure 2.9 below.

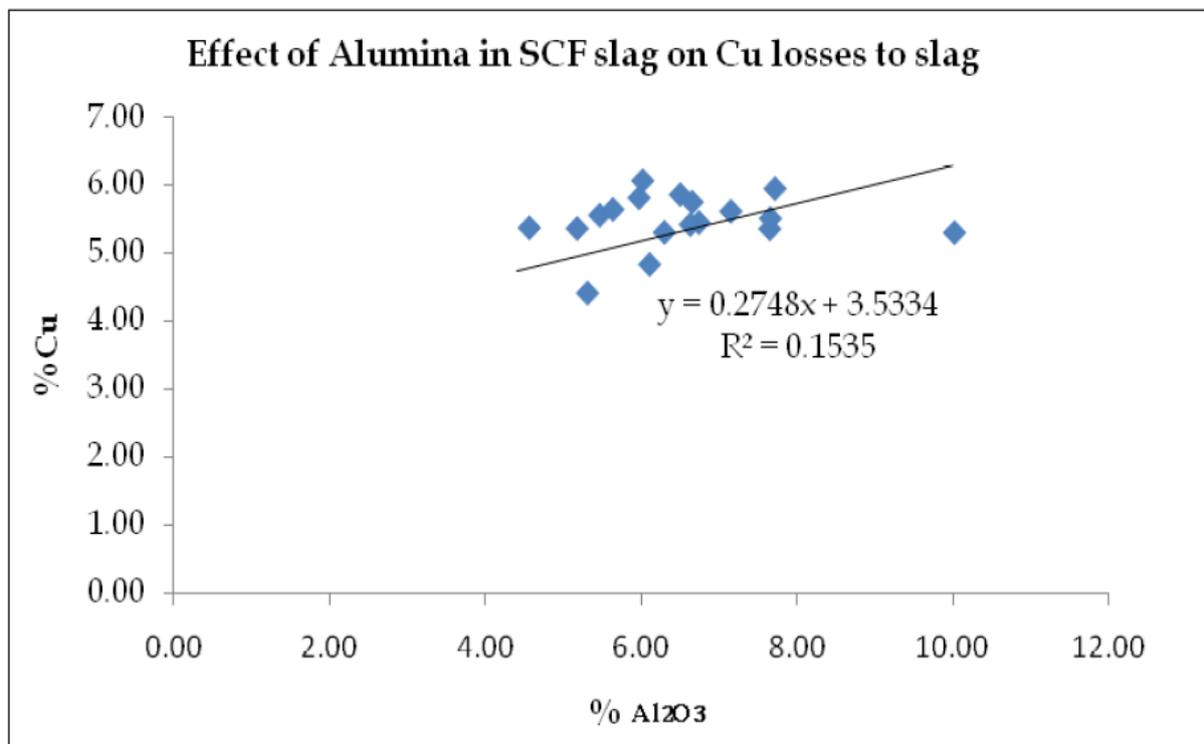


Figure 2.9: Influence of Alumina on control of Cu in SCF (Chikashi, 2011)

### 2.7.5 The influence of Magnesia and Lime on control of Cu in slag

Magnesia ( $MgO$ ) forms a thermally stable silicate called olivine ( $Mg_2SiO_4 - Fe_2SiO_4$ ) at concentrations greater than 3 – 4% in the KCM slag (Chikashi, 2011), resulting in high viscosity slags (Kongoli *et al.*, 2006) and its constituent system species with  $FeO_x$  or  $Fe_3O_4$  are very solid at copper smelting temperatures (Taskinen, 2009). In FSF lime ( $CaO$ ) is used as flux to deter the formation of solid high melting substances such as magnetite ( $Fe_3O_4$ ) and olivine ( $Mg_2SiO_4 - Fe_2SiO_4$ ) and also flux the solid silica.  $CaO$  has an influence on the viscosity of slags, generally, the more the  $CaO$ , to a certain extent, the less is the slag viscosity and this promotes an even settling of blister Cu droplets (Kongoli *et al.*, 2006).

### 2.7.6 Slag Chemistry

Equilibrium composition in molten slags varies considerably with the concentration of influential components in the slag and temperature (Firdu, 2009). For instance, the concentration of metallic oxides such as  $Al_2O_3$ ,  $CaO$  and  $MgO$  greatly affect the amount of dissolved copper or the activity of  $Cu_2O$  and the ferric to ferrous ratio in the slag. In slag cleaning processes, carbon reduction of metallic oxides is selective, irrespective of the extent of concentration of the components in molten slag. For instance, the reduction of  $Cu_2O$  is thermodynamically favoured over  $FeO$  or ferrous oxide reduction, irrespective of its amounts in the slag; also ferric oxide reduction to ferrous oxide takes place rapidly. Copper flash smelting produces typically fayalitic slags, which contain metals in the form of oxides, sulphides, silicates and ferrites (Firdu, 2009).

#### 2.7.6. (a) $Fe - O - SiO_2$ system

Silica and iron oxides are the main constituents of smelting slags and consequently the basic silicate constituent is fayalite ( $2FeO.SiO_2$ ). Copper slag systems can be explained by the  $Fe - O - SiO_2$  equilibrium system (Henao *et al.*, 2009). Figure 2.10 is a phase diagram which shows the variations of the slag types within the  $Fe - O - SiO_2$  system at different  $SiO_2/(SiO_2 + Fe)$  mass ratios and partial pressure of oxygen.

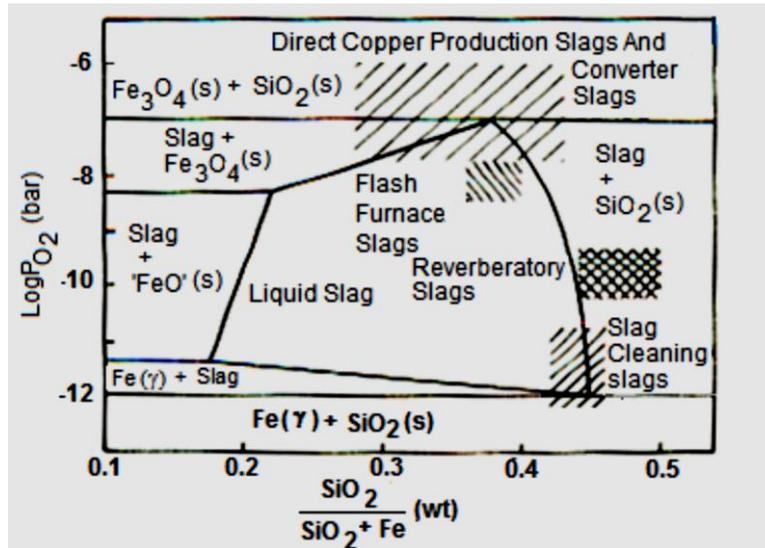


Figure 2.10: FeO-SiO<sub>2</sub> phase diagram at 1523 K showing composition and oxygen pressure of some copper making slags (Henaio et al., 2009)

From the phase diagram, the direct-to-blister copper production slags' minimum oxygen partial pressure is  $10^{-7}$  bar at the Fe<sub>3</sub>O<sub>4</sub> – SiO<sub>2</sub> dual saturation. Also the liquid slags maximum oxygen partial pressure is  $10^{-7}$  bar at the Fe<sub>3</sub>O<sub>4</sub> – SiO<sub>2</sub> dual saturation, and the lowest oxygen partial pressure  $10^{-12}$  bar appears at the Fe – SiO<sub>2</sub> dual saturation. Iron silicate systems are commonly represented through the ternary FeO – Fe<sub>2</sub>O<sub>3</sub> – SiO<sub>2</sub> equilibrium system. This is as a result of the fact that under Cu making process conditions the iron-activity is very low and ferric oxide activity is relatively high (Jalkanen, 2000). Figure 2.11 below shows the Factsage model diagram for the ternary FeO – Fe<sub>2</sub>O<sub>3</sub> – SiO<sub>2</sub> equilibria system.

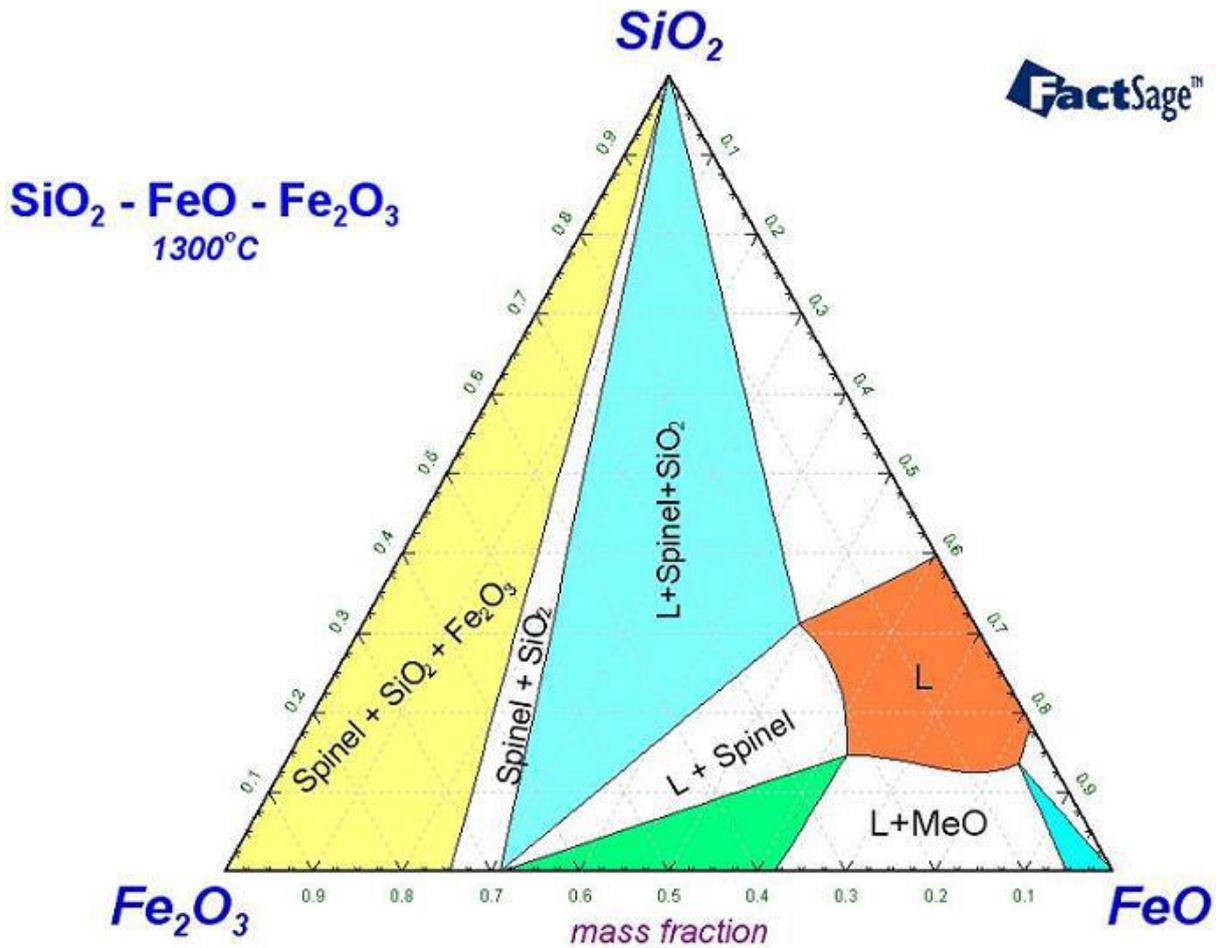


Figure 2.11: Isothermal phase diagram (Factsage model) of  $\text{FeO} - \text{Fe}_2\text{O}_3 - \text{SiO}_2$  system at 1573 K (Firdu, 2009)

From Figure 2.12 below, higher partial pressure of oxygen and lower partial pressure of sulphur entails that the system is composed of components of metals and metal oxides. No sulphides exist in the Cu-Fe-S-O system at  $P_{S_2} < 10^{-6}$  atm, regardless of the changes in the  $P_{O_2}$ . Maintaining the same conditions of  $P_{S_2}$ ; for  $10^{-5} < P_{O_2} < 10^{-4}$  atm, metallic copper, cuprous oxide and ferric oxide exist in the system, and for  $10^{-11} < P_{O_2} < 10^{-8}$  atm only metallic copper and ferrous oxide appear. The Cu-Fe-S-O system can be assumed to be Cu-Fe-O system at  $P_{S_2} < 10^{-6}$  atm, which is the case in the slag cleaning furnace, slag-coke interface where both partial pressures are at their minimum.

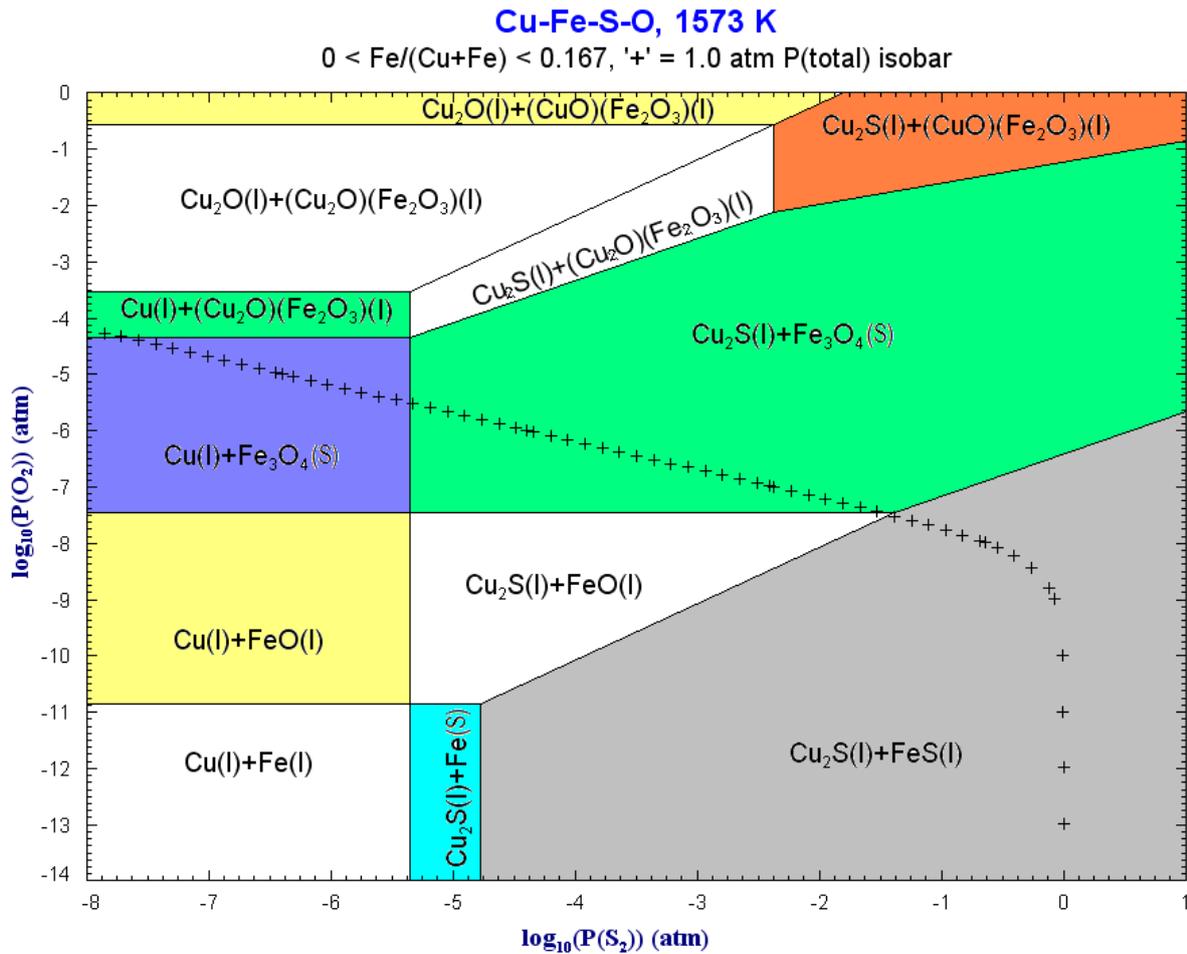


Figure 2.12: Cu-Fe-S-O system at the isothermal condition of 1573K (Firdu, 2009)

### 2.7.6. (b) Oxidic Copper losses

The chemical loss of copper in the slag is mainly in the oxide form i.e.  $\text{Cu}_2\text{O}$ . As discussed, mechanical copper losses can be reduced by tuning the physical properties of the slag. For example a lower slag viscosity can be achieved by developing mechanisms to reduce the amount of magnetite and  $\text{SiO}_2$  in the slag (Schlesinger *et al.*, 2011).

Oxide copper loss in FSF slag is recovered in the SCF using coke as a reductant on top of the slag layer in an electric furnace. Once the molten slag is in contact with the reductant, the selective carbothermic reactions proceed with dependency on temperature and composition variations. Oxidic copper loss is entirely dependent on the activity of the  $\text{Cu}_2\text{O}$  in the slag. This implies that the activity of the metal oxide ( $\text{Cu}_2\text{O}$ ) is the driving force for the dissolution of the corresponding metal in slag (Degterov & Pelton, 1999). Henceforth, loss of copper in slag is enforced by the activity of  $\text{Cu}_2\text{O}$ .

Activity coefficient of metallic oxides is determined as a function of temperature, oxygen partial pressure and slag composition. The influence of temperature on the activity coefficient of  $Cu_2O$  is shown in Figure 2.13 below.

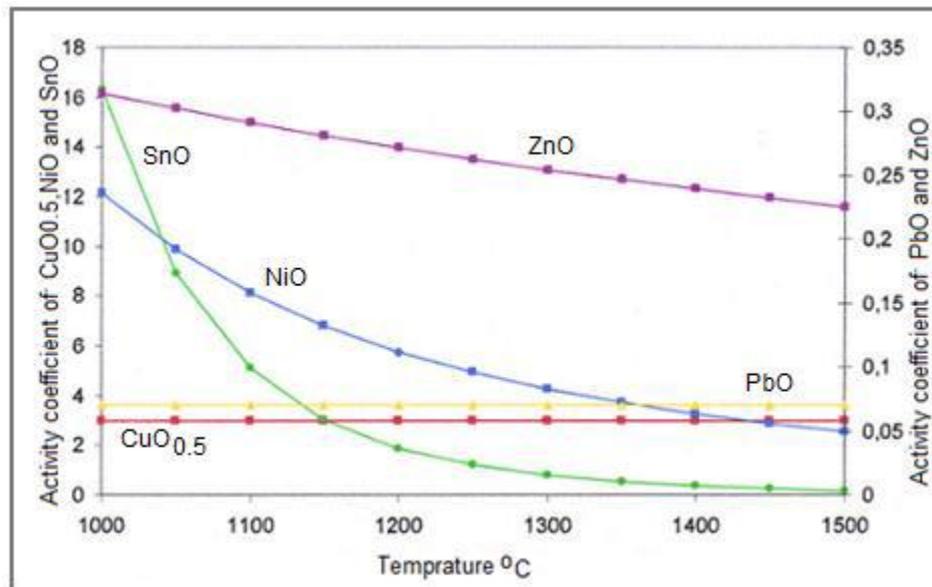


Figure 2.13: Activity coefficient versus temperature of metal oxides at infinite dilution in fayalitic slag ( $FeO - Fe_2O_3 - SiO_2$ , where  $Fe/Si=1.3...5$ ) (Firdu, 2009)

From Figure 2.13, it can be deduced that the activity coefficient of  $Cu_2O$  is not affected by temperature.  $\gamma_{Cu_2O}$  has got a finite value of 2.9 for slags with  $SiO_2$  content ranging from 20 – 38 wt%.

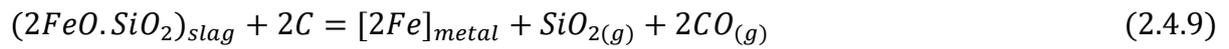
Kim and Sohn (1998), studied on the effects of  $CaO$ ,  $Al_2O_3$  and  $MgO$  additives to the copper solubility and found out that  $Al_2O_3$  has a negligible effect on the solubility of copper in slags,  $CaO$  reduces copper solubility for a given oxygen pressure and  $MgO$  also tends to reduce the solubility even though less effectively.

The radius of  $Ca^{2+}$  ion in  $CaO$  is 0.99 which is almost similar to that of  $Cu^+$  ion in  $Cu_2O$  which is 0.96. As such,  $Ca^{2+}$  occupy sites within the silicate structure, replacing  $Cu^+$  ion, thereby lowering the activity of  $Cu_2O$  (Firdu, 2009).

## 2.8 High Temperature Reduction of FSF slags

At low temperature, selective reduction of copper and iron oxides in SCF carbothermic reaction is expected (Firdu, 2009). This is so, because slag forming oxides such as silica, alumina and limestone are stable approximately up to 1650 °C as depicted from the Ellingham diagram (Appendix A), whereas  $Cu_2O$  and  $FeO$  can be reduced at temperatures as

low as 1260 °C. Cuprous oxide is reduced to metallic copper in the presence of carbon and at temperatures  $T > 1200$  °C. Simultaneously, magnetite is reduced to ferrous oxide and then to iron and iron-silicate decomposes to iron and silica according to the following equations:



FSF slag reduction takes place in a series of direct and indirect reactions of oxides with reducing agents to form a metallic phase and gaseous products. Carbon (from coke) fixes the  $CO/CO_2$  ratio in reaction zone at a given temperature according to the following reaction (Firdu, 2009):



The control of the reduction of metallic oxides is manned by temperature and the prevailing oxygen partial pressure, which is fixed by the  $CO/CO_2$  ratio in the system according to the reaction below (Gonzalez *et al.*, 2005):



CaO, MgO and  $Al_2O_3$  are the minor metallic oxides in the slag and do not compete with iron and copper oxides in the selectivity of carbon reaction. At temperatures above 1260 °C  $Cu_2O$  can be reduced at low CO pressures compared to magnetite, which requires high CO-partial pressure (Gonzalez *et al.*, 2005). Iron silicate, where the activity of FeO is approximately 0.4 at 1260 °C, needs even a higher reducing condition.

Firdu researched on the condition over which the slag cleaning carbothermic reactions stop or Gibbs energy change of reaction (as expressed in equation 2.5.3) turn to a positive value.

$$\Delta G_{reaction} = RT \left[ \ln \left( \frac{a_{product}}{a_{reactant}} \right) - \ln K_p \right] \quad (2.5.3)$$

Where R = universal gas constant

$a_{product}$  and  $a_{reactant}$  = activities of products and reactants, respectively.

$K_p$  = equilibrium constant of the reaction at standard conditions.

The experimental data were used to construct a graph as shown in Figure 2.14 (Appendix B).

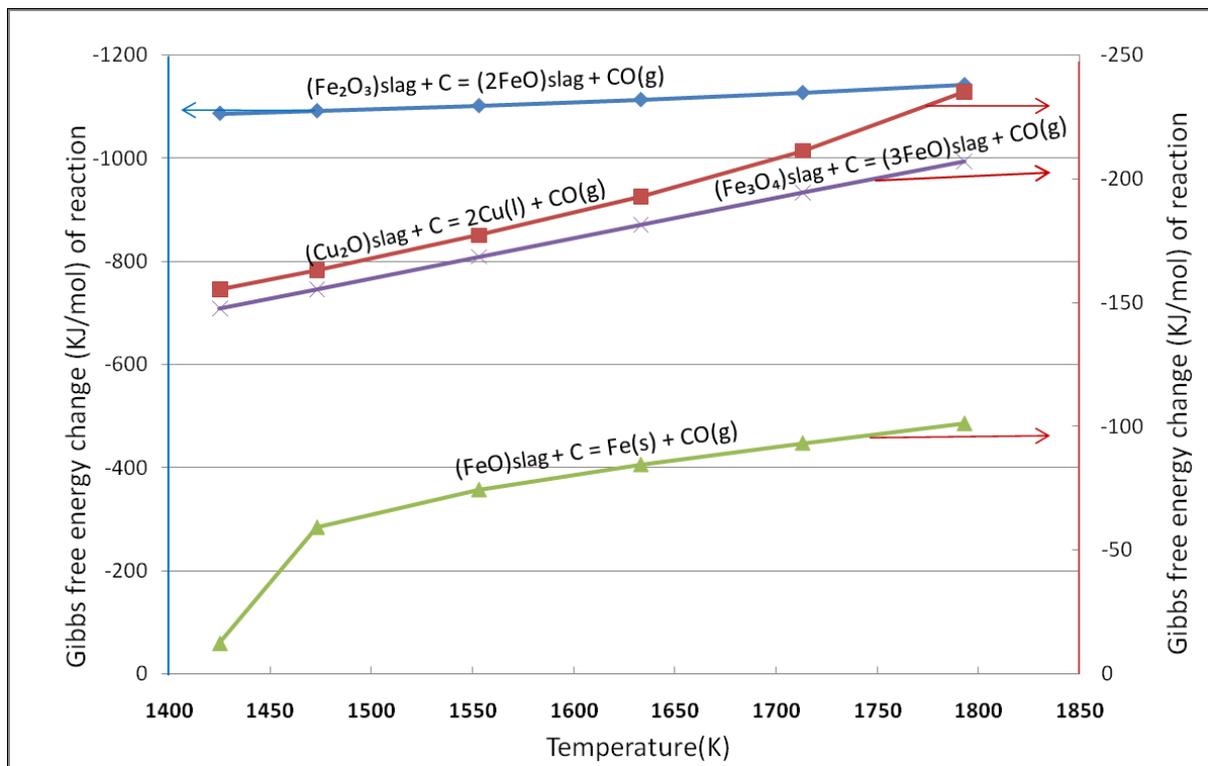


Figure 2.14: Calculated diagram of Gibbs free energy change of the carbothermic reactions at the slag-coke interface (Firdu, 2009)

From the calculated graph, the Gibbs free energy change of the reactions studied generally increased with temperature. However, the reduction of ferric oxide to ferrous oxide was found exceptionally radical, irrespective of the temperature change within the given range (Firdu, 2009).

Ferrous oxide reduction appeared to be significantly improved with temperature rise. The reduction of Cuprous oxide was found to be thermodynamically favored over ferrous oxide reduction. Thus, at given temperature until the concentration of  $Cu_2O$  in slag is very low, copper dominates the growing and detaching metallic phases from the reductant surface.

By searching the zero point of the  $\Delta G_{reaction}$  of equation (2.4.6) (in the developed model) at the expense of dissolved copper in the slag at 1573 K, it has been observed that when the theoretical amount of dissolved copper in slag is less than approximately  $2.10^{-6}$  wt% there is almost no reduction of  $Cu_2O$  in the coke-slag interface. At the same temperature when  $Cu_2O$  wt% is less than 0.27, the reduction of  $Cu_2O$  in the bulk slag by ferrous oxide or iron

terminates. Therefore, after this critical concentration, the reduction may be considered to proceed only through the carbothermic reaction (Firdu, 2009).

### 2.8.1 Cobalt recovery from SCF slags

Carbothermic reduction of FSF slags results in the co-reduction of large amounts of Co together with Cu. Increasing Cu in FSF slags increases the dilution of Co in the slag phase and therefore reduces the degree of Co and Cu co-reduction. Different methods of cobalt recovery from slag have been suggested in the past, including the reduction of slag by solid carbon (Floyd and Mackey, 1981). At KCM, Nchanga smelting operations Co is recovered by the reduction of SCF slag by solid carbon (metallurgical coke). The occurrence of cobalt in slag has been described to be most entirely in oxide form (Floyd and Mackey, 1981). In the reductive smelting of SCF slag with metallurgical coke, it is traditionally assumed that the limiting reaction is the gasification reaction of carbon. The gas plays two important roles:

- 1) Mass transfer of elements from metal to slag by escaping gases (i.e.  $CO_2$ )
- 2) Reduction of oxides by reducing gas ( $CO$ )

Three phases (gas-liquid-solid) co-exist only on their interface, therefore, in an overall reaction involving three or more phases, the rate controlling reaction is that which occurs at an interface between the two phases only.

The reduction time of the slag can be limited by the amount of cobalt oxide contained in the slag (Banda *et al.*, 2002). SCF slag at KCM smelting operations contains about 0.78 % Co. The presence of coke promotes the regeneration of  $CO$  gas through the boudouard reaction (Banda *et al.*, 2002). In the presence of solid carbon, carbon dioxide produced by the reduction reaction forms carbon monoxide through the carbon gasification reaction at the carbon/gas interface according to equation (2.5.1). The carbon monoxide gas produced is then available to react at the slag/gas interface according to the following reaction:



The reaction cycle is completed when the carbon dioxide returns to react once more with solid carbon. In the reduction of fayalitic slags, the reactivity of carbon is an important factor determining reduction rate and the rate limiting reaction in this reduction reaction is the carbon gasification (Banda *et al.*, 2002).

Another aspect is that the cobalt oxide and to a lesser extent, the copper oxide associated with the silicate/ oxide phases are reduced by *Fe* from the alloy to form metallic Co and Cu alloy, resulting in the formation of *FeO* in the slag. Given that this reaction occurs between the metal bath and the overlying slag, the exchange of *Co* and *Cu* with *Fe* will take place in the slag/metal interface (Banda *et al.*, 2002).

## **2.9 Summary of Literature Review**

Approximately 90% of the copper in the earth's crust occurs as sulphide minerals of which the most common is chalcopyrite ( $CuFeS_2$ ) (Davenport *et al.*, 2010). Chalcopyrite is easily flash smelted since the oxidation of the iron and sulphur is exothermic. Chalcocite ( $Cu_2S$ ) and bornite ( $Cu_5FeS_4$ ) which are a characteristic of the Zambian Copperbelt, also occur along with chalcopyrite (Partelpoeg *et al.*, 2010). The major oxide mineral composition of the Zambian Copperbelt are malachite ( $Cu_2(OH)_2CO_3$ ); chrysocolla ( $CuSiO_3 \cdot nH_2O$ ); pseudo malachite ( $Cu_5(PO_4)(OH)_4$ ); cuprite ( $Cu_2O$ ) and tenonite ( $CuO$ ) (Mponda *et al.*, 2010). These oxide minerals are treated mainly through hydrometallurgical processes (Davenport *et al.*, 2010). However, there still remains more work to be done on the pyrometallurgical extraction of copper from mixed oxide and sulphide concentrate mineralogy.

## **3 RESEARCH METHODOLOGY**

### **3.1 Introduction**

The research methodology gives an overview of the materials and methods used to carry out the research.

Consultation and Interviews were part of the research design. The knowledge acquired during literature survey was used to formulate questions which were asked to key informants involved in the smelting process. This included Plant controllers, Metallurgists, Smelter managers and production officials. Data from the interviews was generally limited and not suitable for statistical analysis. Nevertheless, the information assisted in assessing the smelting of sulphide concentrates with ASCu.

### **3.2 Research Setting**

The research was done at Konkola Copper Mines Nchanga smelter in Chingola and the focus was on the FSF and SCF smelting operations.

### **3.3 Sample types and sampling points**

Actual process data on concentrate feed blend, blister Cu product and slag in the FSF operations as well as slag feed to the SCF and the resultant SCF blister and slag products were considered as the study population.

### **3.4 Research Approach**

A comparative research was done by comparing actual process data for a period over which ASCu in concentrate blend was greater than 1% to a period over which ASCu in the feed blend was less than 1% to ascertain the inherent process changes or implications of ASCu concentration variations. The established trends were then validated with literature.

### **3.5 Data Collection**

Actual plant data covering a period of 16 months which was already collected previously and readily available was grouped into two categories; with the first category being data when acid soluble copper as part of the feed concentrate from January to August 2016 was in the range 1.5% - 4.1%. The second category of data was for the period where acid soluble copper in the feed concentrate was less than 1%, spanning from January to August 2015. The following is a list of the collected data in monthly averages:

- FSF feed blend analysis: The data shows the assays of the various constituents of the FSF concentrate feed blend to the direct-to-blister flash smelting furnace
- FSF slag analysis: this is the data for the various slag product constituents after smelting in the FSF operations. The slag from the FSF is the feed to the slag cleaning furnace and as such this data is used as the SCF feed input data.
- FSF blister anode analysis: this data contains the assays of the components in the FSF blister product before the blister Cu undergoes anode refining.
- SCF slag analysis: this is the data for the various SCF slag product constituents. Slag product from the slag cleaning furnace operations is laundered to the cobalt recovery furnace and as such this very data is the feed to the CRF.
- SCF blister anode analysis: this data contains the assays of the components in the SCF blister product before the blister Cu undergoes anode refining.
- Data for the ASCu in concentrate feed for the period January to August 2016.
- CRF operations data: this data consists of SCF slag feed assays, CRF slag assays and the Co alloy assays.

Appendices E1-4 show the details of the collected data.

### **3.6 Material balance calculations**

The material balance is a calculation procedure that basically checks if directly or indirectly measured mass flows are in agreement with mass conservation principles. This balance is of utmost importance and is an indispensable tool for a clear understanding of the mass situation and metallic distributions achieved in the processing plant. In order to use it correctly the following procedure was used:

- Clearly identify the problem to be studied.
- Define a boundary that encloses the entire furnace system under analysis.
- The boundary is chosen in such a way that:
  - a) All relevant flows cross it
  - b) Measurements of the boundary must be possible in an easy and accurate manner.
- Utilising the collected measurements, calculate the mass flow and the metallic distributions.

Material balances for Cu and Co were done for FSF, SCF and CRF to ascertain their distribution or split in various streams. The material balances for the three furnace operations were done in two phases; Phase 1 was for the period January to August 2016 over which the feed concentrates contained ASCu greater than 1% and Phase 2 was for the period January to August 2015 over which the feed concentrates contained ASCu less than 1%. The collected data for the two periods were compared to determine the effects resulting from increasing ASCu in feed concentrate blend. The following is a typical procedure for the mass balance calculations for the month of January 2016:

Basis of calculation = 100 metric tonnes (mt) of feed

*Table 3. 1: January FSF concentrate feed and slag assays*

	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
FEED	24.09	15.06	14.94	2.56	1.74	1.18	20.33	4.06	1.27
SLAG	20.28	23.14	28.71	4.39	3.15	1.23	0.12	4.57	2.14

### **SiO<sub>2</sub> Balance**

Mass of SiO<sub>2</sub> input = mass of SiO<sub>2</sub> in slag phase

$$\begin{aligned}
 \text{SiO}_2 \text{ in slag} &= \frac{\% \text{SiO}_2 \text{ in feed}}{100\%} \times \text{mass of concentrate feed} \\
 &= \frac{14.94}{100} \times 100 \text{ mt} \\
 &= \underline{14.94 \text{ mt}}
 \end{aligned}$$

$$\begin{aligned}
 \therefore \text{Mass of Slag} &= \text{mass of SiO}_2 \text{ in slag} \times \frac{100}{\% \text{SiO}_2 \text{ in slag}} \\
 &= 14.94 \text{ mt} \times \frac{100}{28.71} \\
 &= \underline{52.04 \text{ mt}}
 \end{aligned}$$

### **Cu Balance**

$$\begin{aligned}
 \text{Cu in feed} &= \frac{\text{Assay of Cu in feed}}{100} \times 100 \text{ mt} \\
 &= \frac{24.09}{100} \times 100 \text{ mt} \\
 &= \underline{24.09 \text{ mt}}
 \end{aligned}$$

$$\begin{aligned}
\text{Cu in slag} &= \frac{\text{Assay of Cu in slag}}{100} \times \text{Slag weight} \\
&= \frac{20.28}{100} \times 52.04 \\
&= \underline{10.55 \text{ mt}}
\end{aligned}$$

$$\begin{aligned}
\therefore, \text{Cu in Blister} &= \text{Cu in feed} - \text{Cu in slag} \\
&= 24.09 - 10.55 \\
&= \underline{13.54 \text{ mt}}
\end{aligned}$$

From the calculated weights of Cu in the slag and blister phases, the distribution of Cu in these phases is determined as follows:

$$\begin{aligned}
\% \text{ Cu in slag phase} &= \frac{\text{Weight of Cu in slag}}{\text{total weigh of Cu in feed}} \times 100\% \\
&= \frac{10.55}{24.09} \times 100\% \\
&= \underline{43.79\%}
\end{aligned}$$

$$\begin{aligned}
\% \text{ Cu in blister} &= 100 - \% \text{ Cu in slag} \\
&= 100 - 43.79 \\
&= \underline{56.21\%}
\end{aligned}$$

$\therefore$  the FSF distribution or split of Cu in blister and slag phases is 56.21% and 43.79%, respectively.

The above calculation procedure is done for all other feed species in FSF, SCF and CRF and the distribution of Cu, Co and Fe is established for the period January to August 2016 and the trend is observed and analysed.

### **3.7 Degree of Oxidation profile estimation**

In order to identify the shift in the degree of oxidation as a result of ASCu, the quality of the blister copper in FSF was analysed. Degree of oxidation was estimated by analysing the assays of S, O and Fe in the FSF blister copper product. S, O and Fe profiles in blister copper were constructed for the period January to August 2016. For more accurate estimations, the main focus was centred on S. This was so because concentrate feed is the only source of

sulphur in the FSF operations and as such the S in blister is a more reliable indication of the degree of oxidation. There is little dependence on oxygen in blister for estimating the degree of oxidation because apart from the feed oxygen in blast, some oxygen from the atmosphere infiltrates into the top opening of the FSF reaction zone. The following profiles were estimated:

- 1) Degree of oxidation Vs ASCu
- 2) Degree of oxidation Vs Co in Blister
- 3) Degree of oxidation Vs Cu-in-slag

This was to ascertain process implications resulting from the shift in the degree of oxidation.

### 3.8 Determination of Coke consumption in SCF operations

Coke specific consumption calculations were made in order to ascertain the consumption of coke in the carbothermic reduction operations in SCF operations. Coke specific consumption is the coke consumed per metric tonne of Cu produced in electric furnaces and was determined by the following calculations:

$$\begin{aligned} \text{Daily coke specific consumption} &= \frac{\text{Daily tonnage of coke (mt) consumed}}{\text{Daily tonnage of Cu (mt) produced}} \quad (3.1) \\ &= \text{mt Coke / mt Cu} \end{aligned}$$

$$\begin{aligned} \text{Ave monthly coke specific cons} &= \frac{\sum \text{Daily coke specific consumption (mt)}}{\sum \text{Production days}} \quad (3.2) \\ &= \text{mt Coke / mt Cu} \end{aligned}$$

An analysis of the daily specific coke consumption trend for the month with highest Cu-in-FSF slag was done.

## 4 RESULTS AND DISCUSSIONS

### 4.1 Introduction

The effects of ASCu on FSF, SCF and CRF operations are established and discussed in this section. In order to determine the distribution of Cu and Co in the blister and slag streams of the operations of the FSF and SCF operations, as well as the cobalt alloy and slag streams of the CRF operations, mass balance calculations were done for the period January to August 2016 as well as January to August 2015 and the results are presented in Appendices C.1-16 and Appendices D1-2.

### 4.2 Effects of ASCu on FSF Operations

#### 4.2.1 Effects of ASCu on the distribution of copper in the process streams

Figure 4.1 below shows the mass balance results for the split of feed Cu to the FSF blister and slag streams for the two periods 2015 and 2016.

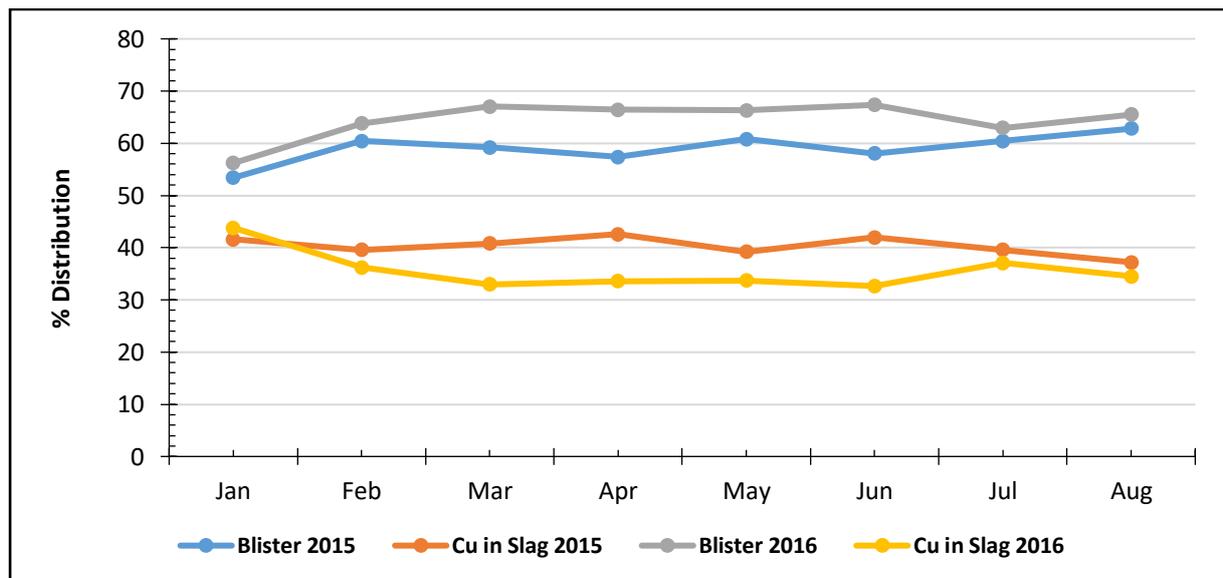


Figure 4.1: The percentage split of feed copper in FSF blister and slag streams

From Figure 4.1, the highest split of feed Cu in FSF operations for the 2016 period was in the month of March with 67% Cu to the blister phase and 33% Cu to the slag phase. For the 2015 period, 65% Cu reported to the blister phase with 35% Cu to the slag phase in the month of August. Generally, the split of Cu to the blister phase was higher throughout the 2016 period compared to the 2015 period. An analysis of the variation of Cu in slag with ASCu is presented in Figure 4.2.

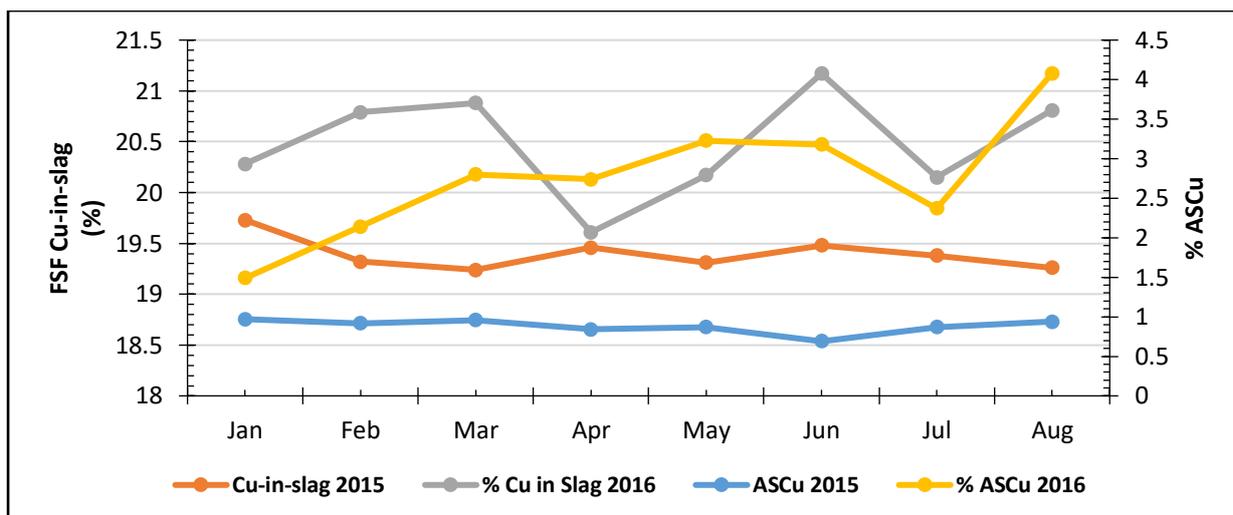


Figure 4.2: Variation of Cu-in-FSF slag with changes in ASCu in concentrate feed

ASCu in the 2015 period is ranging from 0.6% to 0.92% in the feed concentrate i.e. ASCu is less than 1% throughout the period as depicted in Figure 4.2. The observed trend for the year 2016 period as depicted in Figure 4.2, shows that in FSF operations Cu-in-slag generally increases with increasing ASCu in the concentrate feed. From the above graph, as ASCu in concentrate increased from 1.5% in January to 2.9% in March, loss of Cu to the slag increased also from 20.2% to 20.9% Cu-in-slag. In the month of April, as ASCu drops to about 2.7% in concentrate feed, a decrease in Cu-in-slag to 19.6% is observed.

#### 4.2.2 Effects of ASCu on the degree of oxidation and blister quality in FSF.

Figure 4.3 shows the variation of Cu-in-slag with % S in blister copper at Olympic Dam smelter (Hunt et al., 1999):

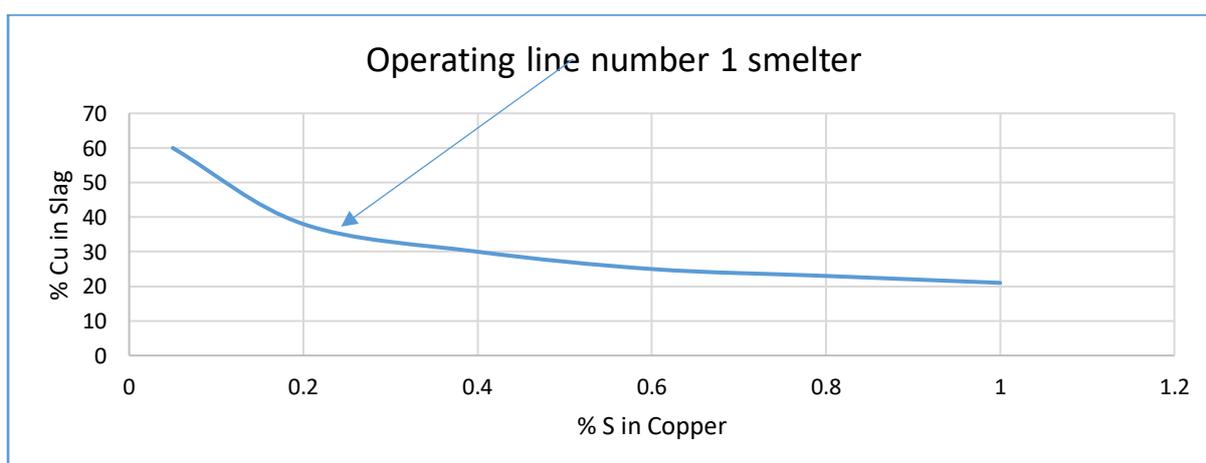


Figure 4.3: % Cu-in-slag vs %S-in-Copper at Olympic Dam Smelter (Hunt et al., 1999) Cu-in-slag is seen to increase with decreasing %S in Copper.

S in blister Cu has been established to be a very excellent and reliable indicator of the degree of oxidation in FSF operations as compared to O-in-blister (Hunt *et al.*, 1999). The solubility of S-in molten copper was established to be about 1% (Sharma & Chang, 1980). In a study by Hunt *et al.* (1999), at Olympic Dam Smelter, Cu in slag is seen to increase with decreasing %S in Cu as shown in Figure 4.3.

The effect of ASCu on the degree of oxidation is shown in Figure 4.4 below.

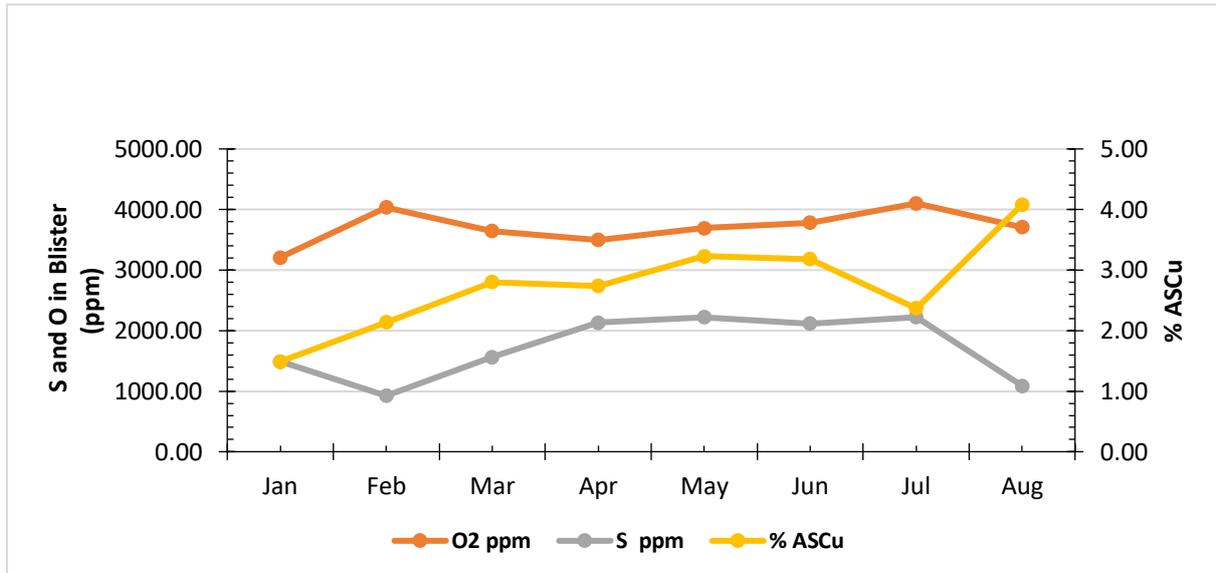
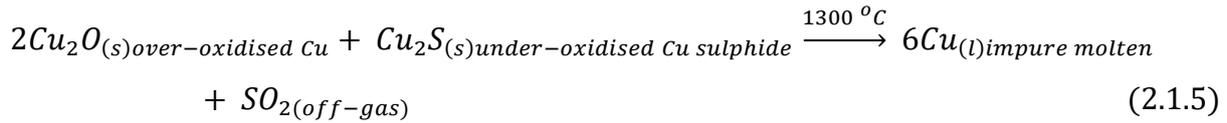


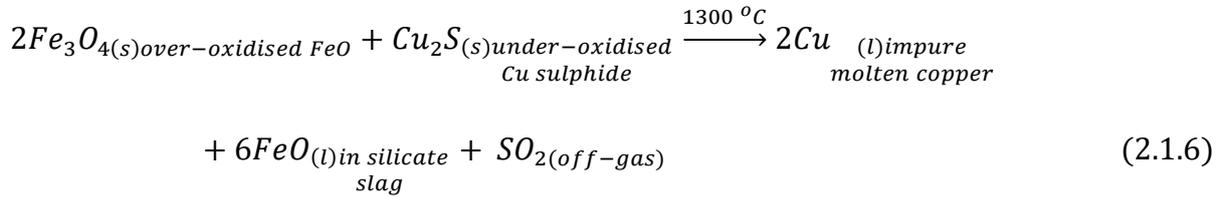
Figure 4.4: Effect of ASCu on the degree of oxidation (2016)

From Figure 4.4, in the month of February ASCu was 2.14% with a corresponding 1000 ppm S in blister. As ASCu increased to 2.74% in April there was an increase in S in blister to 2000 ppm. This increase of S-in-blister is an indication of the decrease in the degree of oxidation. Generally, as ASCu increases in FSF operations S in blister increases showing that the degree of oxidation decreases. The shift in the degree of oxidation in FSF as a result of ASCu, has implications on Cu-in slag as illustrated in the observed trend in Figure 4.5 below.

From Figure 4.5, the highest degree of oxidation was in the months of February and August with S-in-blister at 1000 ppm. During, these months Cu-in-slag was at 21% for the two months. The month of April shows a lower degree of oxidation with S-in-blister at 2000 ppm and the corresponding Cu-in-slag at 19.6%. Furthermore, under-oxidation or lowering of the degree of oxidation favours the formation of molten  $Cu_2S$  (white metal) layer built up between the molten copper and molten slag layer (Hunt *et al.*, 1999), which has the potential to react with slag by reactions such as:



And



These reactions produces  $SO_2$  beneath the slag layer and causes slag foaming to occur and as such potentially serious operational problems emanating from foaming do occur (Davenport *et al.*, 2010).

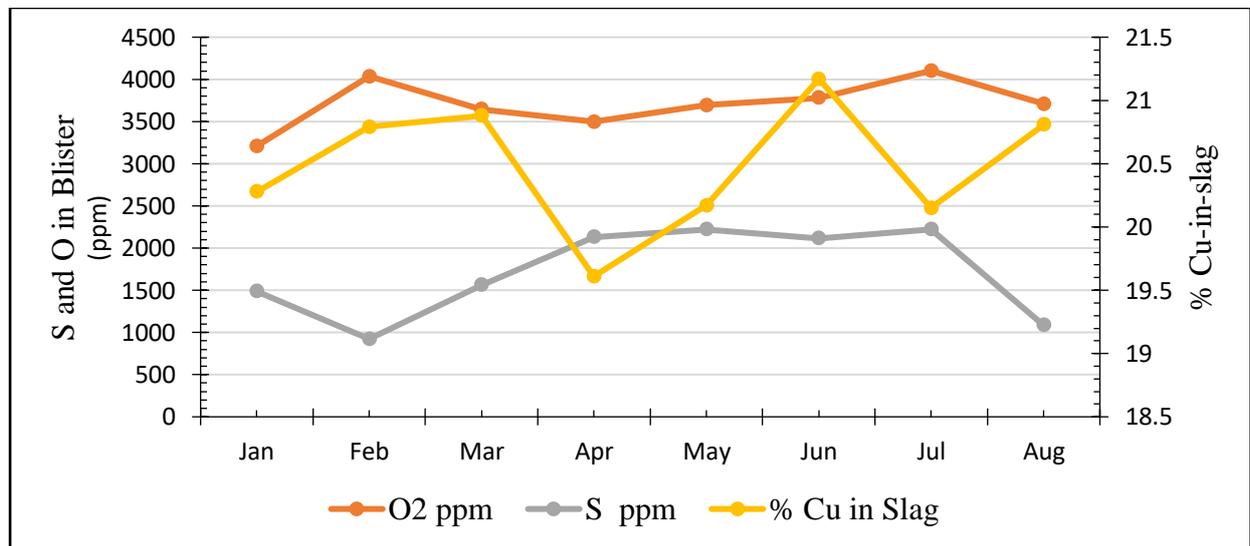


Figure 4.5: Effect of shift of the degree of oxidation on FSF Cu-in-slag (Jan – Aug 2016)

Generally, the trend in Figure 4.5 shows that as the degree of oxidation goes up i.e. low S in blister, the loss of Cu to the slag phase increases. This is consistent with established results of the study by Hunt *et al* (1999) at Olympic Dam smelter as illustrated in Figure 4.3.

Details of the blister quality are presented in Appendices E2 and E4. The shift on the degree of oxidation has implications on the split of Co to the blister phase. An established trend of Co-in-blister as a result of ASCu is shown in Figure 4.6 below.

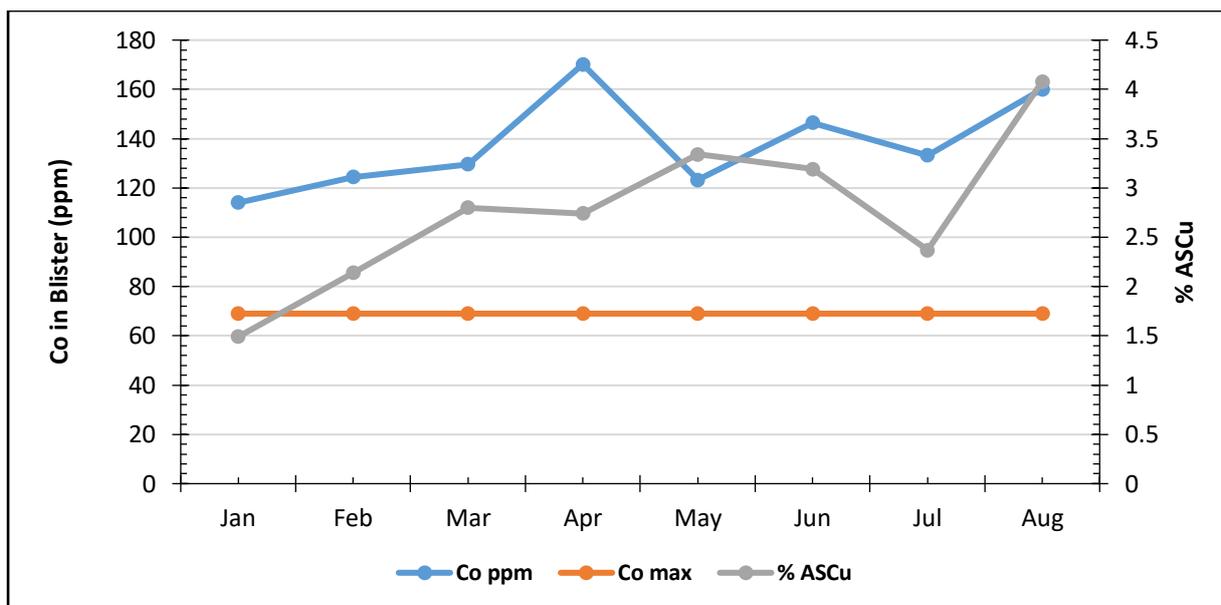


Figure 4.6: Effect of ASCu on Co deposition in FSF Blister (Jan – Aug 2016)

The trend for the period January to August 2016 generally shows that Co-in-blister increases with increasing ASCu. This is so because ASCu lowers the degree of oxidation as evidenced in the month of April in Figure 4.4 above, and as such the resultant under-oxidation pushes more Co to deposit in the blister phase. The maximum set target for Co-in-blister of 69ppm in FSF operations has been entirely surpassed as shown in figure 4.6, with the highest Co-in-blister at 170 ppm being in the month of April (a result of under-oxidation). This lowers the blister quality, since Co-in-blister is an impurity element. The effect of ASCu on the degree of oxidation and blister quality is considered negligible when in concentrations lower than 1%, as is the case for the 2015 period.

### 4.3 Effects of high oxide copper in SCF operations

Slag cleaning furnace is essentially a stage for scavenging Cu in FSF slag through carbo-thermic reduction. The objective of the SCF operation is to reduce the copper in the FSF slag to 3 – 5%. Figure 4.7 below, shows the split of the total Co feed in the slag cleaning furnace operations in blister and slag phases based on the mass balance calculations for the period January to August 2015 and 2016.

The split of Co to the slag phase in 2016 was higher than in the 2015 period. In 2016, approximately 80 % of the total Co in feed reported to the slag phase from January to March. Almost all the feed Co reported to the slag phase in the month of April. Less than 20% of the feed Co reported to the blister phase in the period May to August.

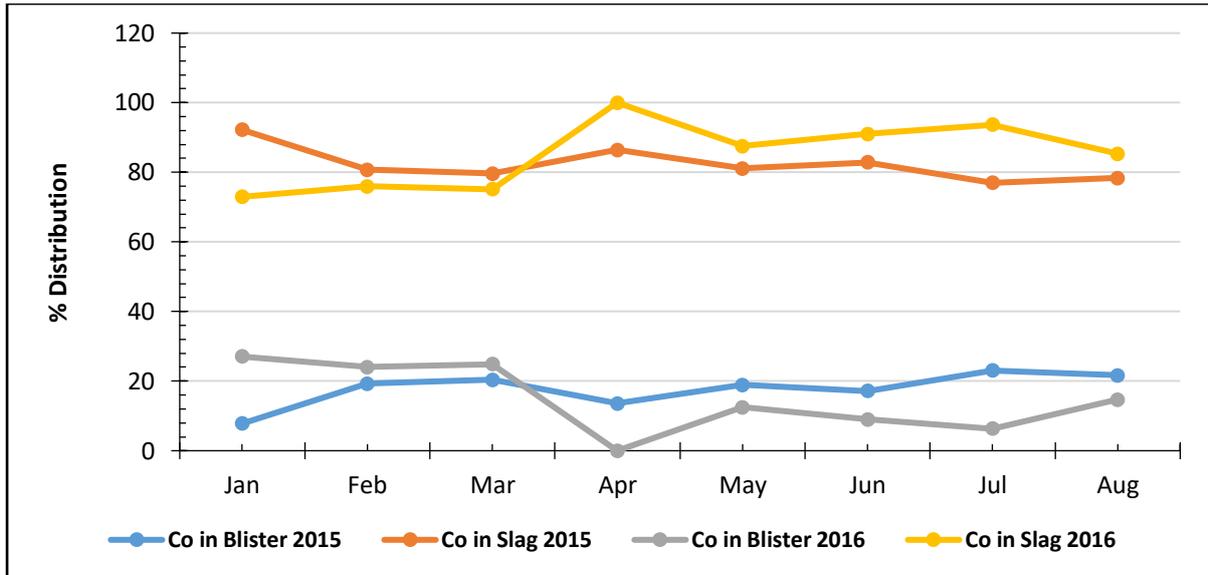


Figure 4.7: The distribution of Co in SCF slag and blister phases

Figure 4.8 below, shows the split of the total Cu feed to the slag cleaning furnace operations in blister and slag phases based on the material balance calculations for the 2015 and 2016 periods.

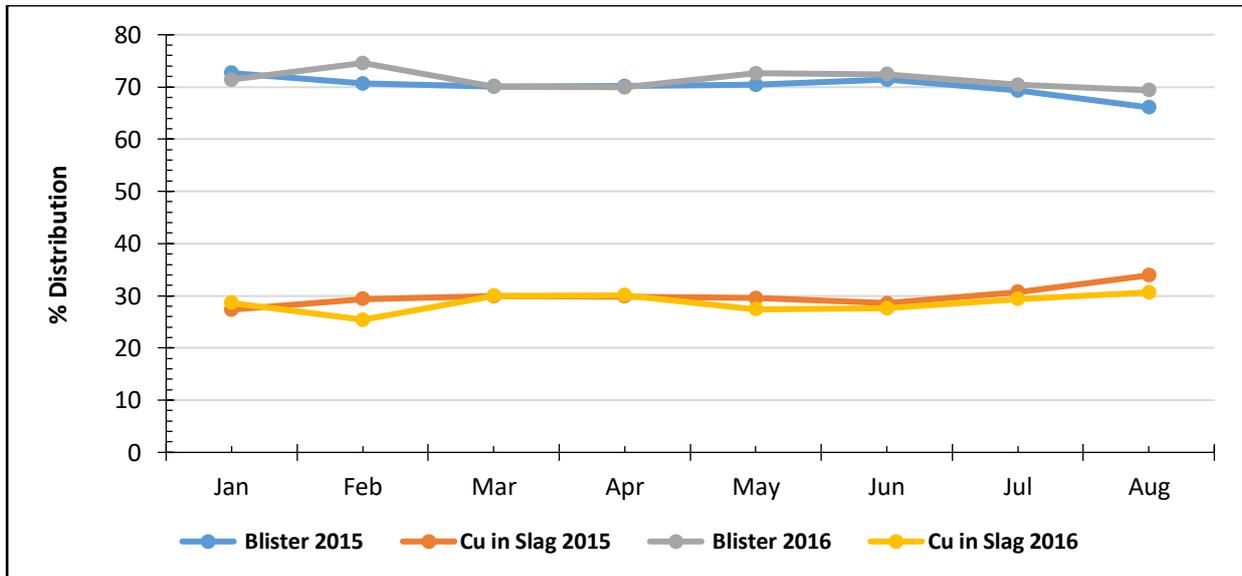


Figure 4.8: The split of Cu in SCF operations

From the graph above, the split of Cu in the SCF operations is very similar for the two periods, ranging from 70 – 75% Cu and 25 – 30% Cu, in blister phase and slag phase, respectively.

### 4.3.1 Effects of ASCu on SCF Blister quality and temperature

From the thermodynamic understanding of the reduction process using Ellingham diagram in Appendix A,  $Cu_2O$  is reduced to  $Cu$  preferentially as compared to the reduction of  $CoO$  to  $Co$ . However, with high chemical copper losses to the slag phase as a result of the higher degree of oxidation in FSF operations,  $Co$  and  $Cu$  co-reduction in SCF increases resulting in high  $Co$  in SCF blister above the maximum threshold point of 1800 ppm.

Figure 4.9 below shows the variation of  $Co$  deposition in the SCF blister phase with  $Cu$  in the input FSF slag. The trend shows that  $Cu$ -in-slag in 2015 is relatively low compared to 2016, with fluctuations very close to 19.5% for the 2015 period. The degree of  $Co$ - $Cu$  co-reduction is high for 2015 compared to 2016. However, with high  $Cu$ -in-slag as is the case for 2016, slag fluidity tends to increase and as a result the department of  $Co$  to the slag phase increases (Chikashi, 2011).

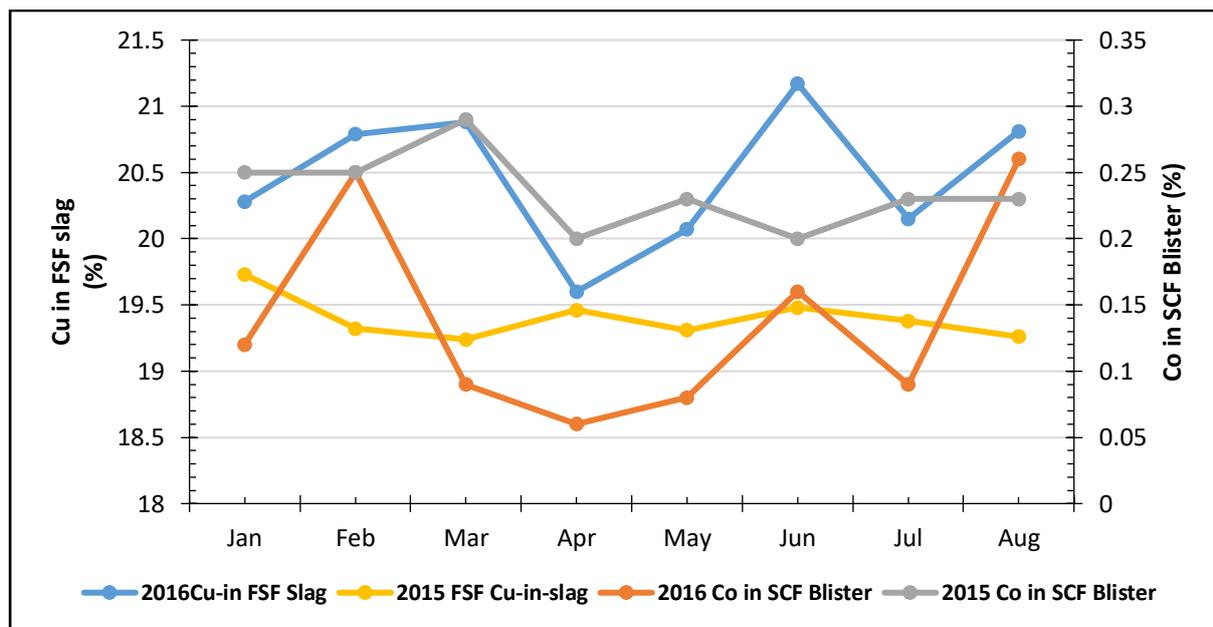


Figure 4.9: Variation of  $Co$ -in-SCF blister with  $Cu$ -in-FSF slag

The trend for 2016 shows that as  $Cu$ -in FSF slag increases,  $Co$ - $Cu$  co-reduction increases with an effect of increasing  $Co$  in the SCF blister phase, thus, lowering the quality of the blister product. As  $Cu$ -in FSF slag decreases to 19.5% in April for instance,  $Co$ - $Cu$  reduction decreases resulting in a decrease in  $Co$ -in blister to 0.06%  $Co$  and hence improved blister quality. High levels of  $Co$ -in-SCF blister copper (above 1800ppm) has two negative implications:

- 1) Co is an impurity element in Blister copper product and thus lowers the blister quality.
- 2) Co is a high melting point metal ( $1495^{\circ}C/1768 K$ ) compared to Cu ( $1083^{\circ}C/1356 K$ ). As such it causes temperature drop in blister product and as such blister Cu crystallises easily and thus causes blister tapping challenges (Mponda *et al.*, 2010).

#### 4.3.2 Effects of increased Cu-in-slag on Coke consumption

Table 4.1 (below) shows the calculated values for the average coke specific consumption compared to the blend plan (BP) specific consumption (mt coke/mt Cu) for the 2016 period.

Table 4.1: Average coke specific consumption for the 2016 period

Month (2016)	Cu-in-FSF slag (%)	Coke specific cons (Actual) (mt coke/ mt Cu)	BP Coke specific cons (mt coke/ mt Cu)
Jan	20.3	0.11	0.11
Feb	20.8	0.14	0.13
Mar	20.9	0.14	0.12
Apr	19.6	0.11	0.12
May	20.1	0.11	0.12
Jun	21.2	0.14	0.12
Jul	20.2	0.12	0.12
Aug	20.8	0.14	0.13

Figure 4.10 below shows the daily consumption trend of coke during the month of June 2016, in which the average Cu-in-FSF slag for the month was at 21.2% Cu.

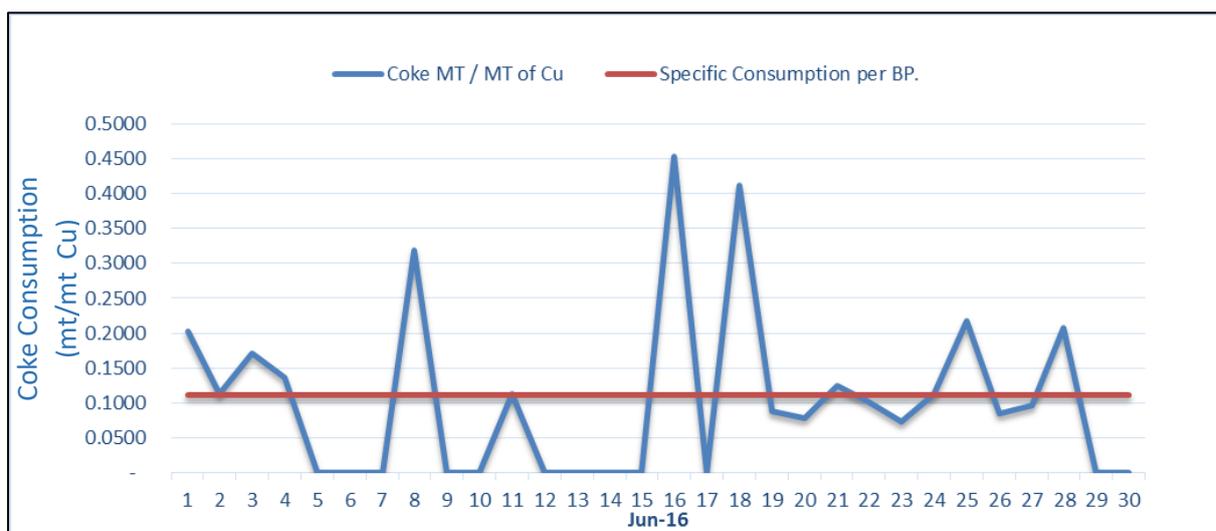


Figure 4.10: Daily specific coke consumption trend for the month of June 2016

From Figure 4.10, it is observed that more often than not the coke consumption per tonne of Cu produced was greater than the specific consumption per blend plan of 0.12 mt/mt Cu. Average coke specific consumption for the month of June 2016 was 0.14 mt/mt Cu against a daily blend plan specific consumption of 0.12mt coke/mt Cu. Generally an increase in Cu-in-slag from FSF operations increases the consumption of coke in SCF operations.

#### 4.4 Effects of ASCu on CRF Operations

The recovery of cobalt to the slag phase in FSF and SCF is very sensitive to quite a set of process conditions. In a research done by Takeda *et al* (1995), cobalt distribution can be expressed mathematically in its simplest form as the cobalt partition coefficient ( $L_{Co}$ ):

$$L_{Co} = \frac{(\%Co)}{[\%Co]} \quad (4.1)$$

Where [ ] and ( ) represents the blister copper and slag phases respectively. The objective therefore, is always to achieve a partition ratio that is as large as possible; hence a good cobalt distribution in FSF and SCF is one that has more cobalt in the slag phase than the blister phase. The idea is to send minimum Co to the blister phase and to capture the maximum amount of Cu in the FSF and SCF blister phases. This is so because payables of Co are lower in the blister anodes that go to the refinery for copper cathode production, likewise payables of Cu in the Co-Cu-Fe alloy from CRF are lower. Process data in Appendix D.2 was used to plot the partitioning of Co-in FSF and SCF operations as shown in Figure 4.11 below.

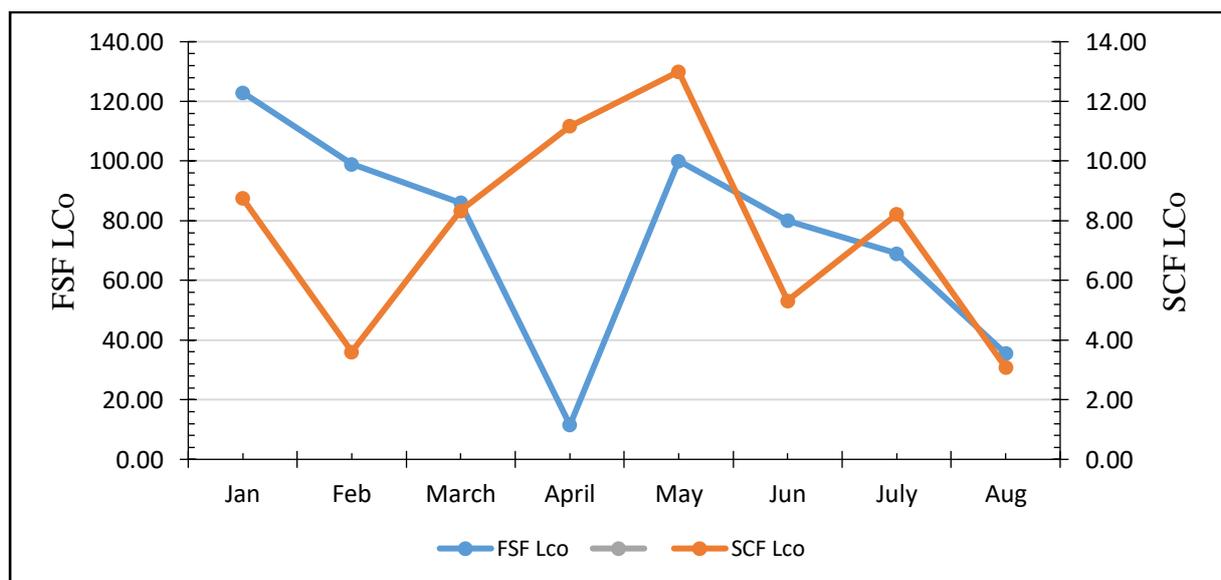


Figure 4.11: Cobalt partitioning in FSF blister and slag phases

Mathematically, from equation 4.1, the higher the  $L_{Co}$  value the higher the distribution of cobalt in the slag phase and hence the higher the cobalt going to the cobalt recovery furnace (CRF). Figure 4.11 shows that Co partitioning was excellent in the months of January and May in both the FSF and SCF operations. In January,  $L_{Co}$  in FSF and SCF were 123 and 8.8 respectively. Also in May,  $L_{Co}$  in FSF and SCF were 100 and 13 respectively. These high values imply that the split of Co to the slag phase in both FSF and SCF operations was excellent. There was very poor partitioning of Co to the slag phase in FSF in April as shown in the graph, with  $L_{Co}$  at 11.5, implying that most of the cobalt was lost to the FSF blister phase. This loss of Co to FSF blister is a consequence of under-oxidation or lowering of the degree of oxidation emanating from increase in ASCu as shown in April from Figure 4.4, which transfers more Co to the blister phase. Henceforth, the net effect is the lowering of the overall Co recovery in the whole smelting operations.

## 5 CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

The effects of ASCu on FSF, SCF and CRF operations were investigated using the process data for the 2016 period in which ASCu was ranging from 1.5% to 4.1% and comparing with process data for the previous 2015 period over which ASCu was entirely below 1% in the concentrate blend. The findings can be summarised as follows:

- At ASCu levels less than 1%, Cu-in-slag in FSF operations has a negligible dependence on ASCu i.e. the values of Cu-in-slag remained almost the same at below 19.5% Cu. With ASCu at 1.5%, the split of Cu in FSF as established from the material balance calculations was 67% Cu to blister phase and 33% Cu to slag phase. ASCu in concentrate blend ranging from 1.5% to 4% results in increases in Cu-in-slag in the range 19.6% to 21.2%. On the other hand, the set target of 69ppm Co in blister is entirely surpassed with Co in blister going as high as 180 ppm.
- From the analysis of S in FSF blister, the FSF degree of oxidation was found to be very sensitive to variations of ASCu in concentrate blends. When ASCu increased, sulphur in blister increased, an indication of the lowering of the degree of oxidation which in turn favours the deportment of Co to the blister. For instance at 2.7% ASCu, the sulphur level was found to be at 2200 ppm with a subsequent 170.2 ppm Co reporting to the blister which is above the set target of 69 ppm.
- The split of Cu in SCF operations was found to be 70% and 30% to the blister and slag phases respectively.
- The split of Co in SCF operations was found to vary with concentration of Cu-in-feed slag. At Cu-in-slag greater than 19.5%, Co splits at 88% and 12% in slag and blister phases respectively. At Cu-in-slag less than 19.5%, Co splits at 80% and 20% in slag and blister phases respectively. This shows that the degree of Co-Cu co-reduction is high at low levels of Cu in slag and low at high levels of Cu-in slag. This implies that the loss of Co to the blister phases increases when Cu-in-slag decreases. Consequently, the overall Co recovery throughout the smelting operations is reduced as a result of losses to the blister phase in FSF and SCF operations.
- The calculations on specific coke consumption show that, per tonne of copper produced, the coke requirement for carbothermic reduction in SCF operations is

affected by the feed FSF slag composition. Per tonne of copper produced, however, the SCF coke consumption increases with increasing % Cu-in-FSF slag feed.

## **5.2 Recommendations**

The effects of ASCu established in this research are of fundamental nature in understanding the management and control of flash smelting feed and slag to levels which will enable better control of Cu in slag, smoother operation of the slag cleaning furnace and cobalt recovery.

There are several factors and properties of concentrate feed, smelting parameters related to FSF Cu loss to slag phase and the deportment of Co to the blister phase and subsequent decrease in Co recoveries. For example, factors such as oxygen partial pressures relate to Cu and Co losses and S in concentrate blend relate to direct to blister flash smelting energy requirements. These factors need to be investigated using an appropriate software package.

The direct to blister flash smelting operations are very sensitive to changes in the feed composition, but with a wide ASCu tolerance levels and as such there is need to investigate the extent over which ASCu can be utilised in the sulphide concentrate smelting operations.

This study opens up opportunities to experimentally study the changes in slag chemistry with varying ASCu concentrations in the concentrate blend. Further work on thermodynamically assessing the effects of ASCu on the flash and slag cleaning operations is recommended.

## REFERENCES

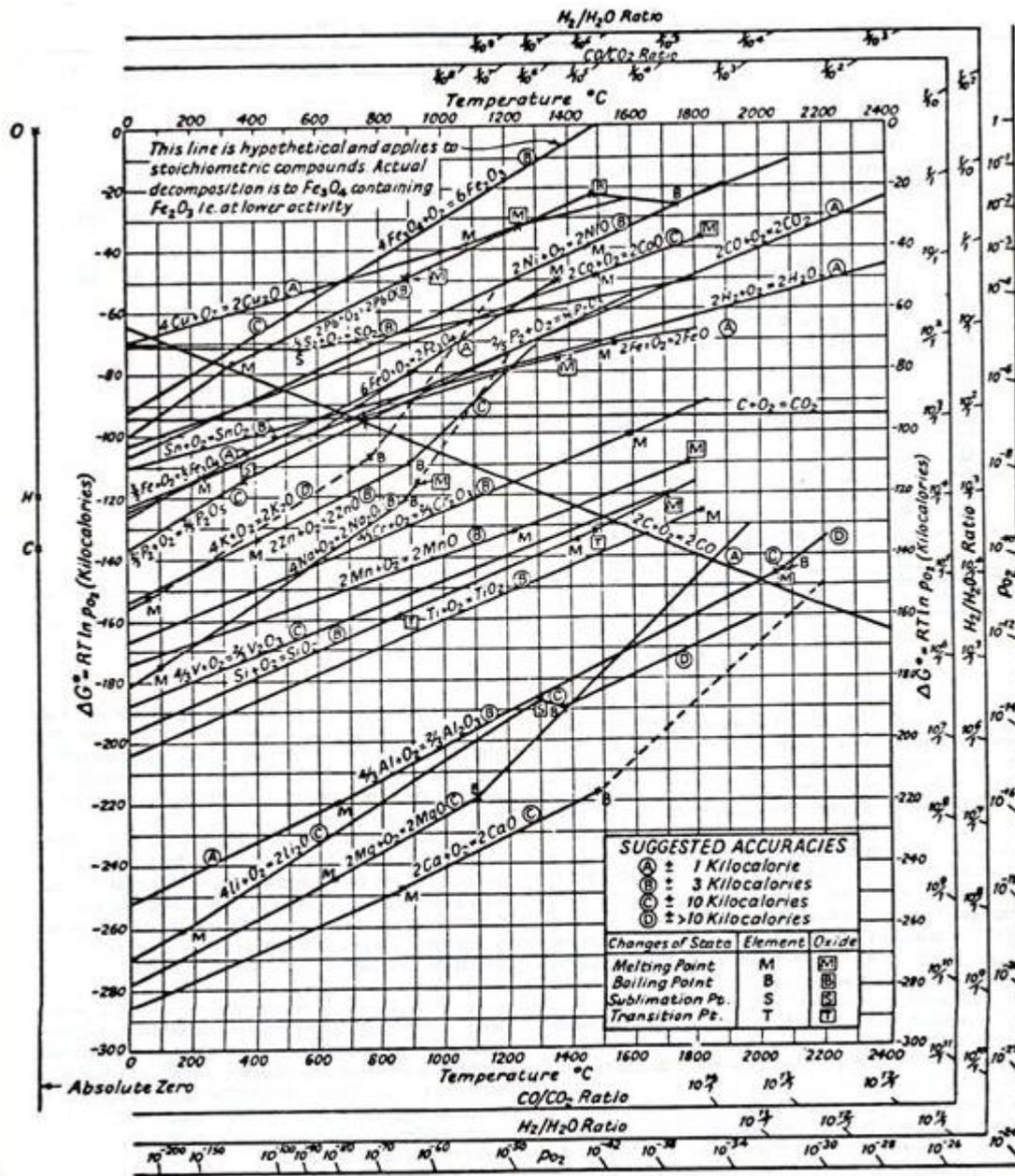
- Ashman, D. W., McKelliget, J. W., & Brimacombe, J. K. (2013). Mathematical model of bubble formation at the tuyeres of a copper converter. *Canadian Metallurgical Quarterly*.
- Banda, W., Morgan, N., & Eksteen, J. J. (2002). The role of slag modifiers on the selective recovery of cobalt and copper from waste smelter slag. *Minerals Engineering* 15, 899-907.
- Boris, V. L. (2000). Mechanism of Carbothermical reduction of Iron, Cobalt Nickel and Copper oxides. *Thermochimica Acta* (pp. 1-3). Russia: Elsevier.
- Byszynski, L., Garycki, L., Gostynski, Z., Studolski, T., & Urbanowski, J. (2010). Present and future modernization of metallurgical production lines of the Glogow copper smelter. *Copper 2010, Vol 2: Pyrometallurgy I* (pp. 631-647). Germany: Clausthal-Zellerfeld.
- Chikashi, H. M. (2011). Influence of slag composition on reduction control and operations of the slag cleaning furnace at KCM, Zambia. *Southern African Institute of Mining and Metallurgy*.
- Czemecki, J., Siniszek, Z., & Miczkowski, Z. (2009). *A proposal for a two-stage process from flash furnace for increasing the efficiency of HM Glogow 2*. Glimice, Poland: Institute of Non-Ferrous Metals.
- Czernecki, J., Smieszek, Z., Miczkowski, Z., Dobrzanski, J., Bas, W., & Szwancyber, G. (1999). The process flash slag cleaning in an electric furnace at Glogow II copper smelter. *9th international flash smelting congress* (pp. 375-389). Espoo, Finland: Outokumpu Technology.
- Czernecki, J., Smieszek, Z., Miczkowski, Z., Kraweic, G., & Gizicki, S. (2010). Problems of lead and arsenic removal from copper production in a one-stage flash-smelting process. *Copper 2010, Vol. 2: Pyrometallurgy I*, (pp. 669-683). Clausthal-Zellerfeld, Germany.
- Davenport, W. G., James, D. M., King, M. J., & Partelpoeg, E. H. (2010). *Flash smelting, analysis, control and optimization*. New York, USA: Wiley.
- Davenport, W. G., King, M., Schelesinger, M., & Biswas, A. K. (2002). *Extractive Metallurgy of Copper*. Pergamon.
- Degterov, S. A., & Pelton, A. P. (1999). A thermodynamic database for copper smelting and converting. *Process Metallurgy and Materials Processing Science*.
- Dobrzanski, J., & Kozminski, W. (2003). Copper smelting in KGHM. *Pyrometallurgy of Copper*, (pp. 669 -683). Montreal, Canada.
- El-Rassi, E. P., & Utigard, T. A. (2000). Rate of slag reduction in a laboratory electric furnace - Alternating vs Direct current. *Metallurgical and materials transactions B, Vol 31B*.
- Eric, R. H. (2004). Slag properties and design issues pertinent to matte smelting electric furnaces. *Journal of the South African institute of Mining and Metallurgy*.
- Firdu, F. T. (2009). *Kinetics of copper reduction from molten slags*. Helsinki University of Technology; Department of Material Science and Engineering.

- Floyd, J. M., & Mackey, P. J. (1981). Developments in Pyrometallurgical treatment of slag: A review of current technology and physical chemistry. *Extractive Metallurgy*, 345-371.
- Goldstein, E. A., & Reginald, M. E. (2010). Chemical kinetics of Copper oxide reduction with carbon monoxide. *Proceedings of Combustion Institute*. USA: Elsevier.
- Gonzalez, C., Parra, R., Klenovcanova, A., Imris, I., & Sanchez, M. (2005). Reduction of Chilean copper slags: a case of waste management project. *Scandinavian Journal of Metallurgy*, 143-149.
- Henao, H., Hayes, P., Jak, E., George, K. D., & Nexhip, C. (2009). Investigation of copper smelting slags in the FeO-Fe<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-CaO-MgO-Al<sub>2</sub>O<sub>3</sub> system at fixed oxygen potential. *Molten 2009*, (pp. 93 - 100). Santiago, Chile.
- Hunt, A. G., Day, S. K., Shaw, R. G., Montgomerie, D., & West, R. C. (1999). Start up and operation of the #2 direct-to-copper flash furnace at Olympic Dam. *9th international flash smelting congress* (pp. 375-389). Espoo, Finland: Outokumpu Technology.
- Jalkanen, H. (2000). *Studies on matte-slag equilibria in the system Cu-Fe-S-O-SiO<sub>2</sub>*. Helsinki University of Technology, Institute of Process Metallurgy.
- Kim, H. G., & Sohn, H. J. (1998). Effects of CaO, Al<sub>2</sub>O<sub>3</sub> and MgO additives to the copper solubility, ferric/ferrous ratio, and minor element behaviour of iron-silicate slags. *Materials and Metallurgical Transaction B. Vol 29B*.
- Kongoli, F., McBow, I., & Yazawa, A. (2006). Phase relations of ferrous calcium silicate slag and its possible application in the industrial practice. *Sohn International symposium, Advanced processing of metals and materials, Vol-8 International symposium on sulphide smelting*.
- Makinen, T., Pienimaki, K., Dhulipala, P., & Mponda, E. (2010). Elegant solution for challenging Zambian raw material base. *Proceedings of Copper*, (pp. 1-2). Finland.
- Moskalyk, R. R., & Alfantazi, A. M. (2003). Review of pyrometallurgical practice: today and tomorrow. *Minerals engineering*, 893-919.
- Ranasinghe, D. J., Russel, R., Muthuraman, R., & Dryga, Z. (2010). Process optimization by means of heat and mass balance based at Olympic Dam. *Copper 2010, Vol 3: Pyrometallurgy II* (pp. 1063-1078). Germany: Clausthal-Zellerfeld.
- Schlesinger, M. E., King, M. J., Sole, K. C., & Davenport, W. G. (2011). *Extractive Metallurgy of Copper*. New York: Elsevier.
- Seetharaman, S. (2005). *Fundamentals of Metallurgy*. Cambridge: Woodhead Publishing Limited.
- Sharma, R. C., & Chang, Y. A. (1980). A thermodynamic analysis of the copper-sulphur system. *Met. Trans B.11*, 575-583.
- Simunika, N. (2014). *Pyrometallurgy Basics: Theory and Practice*. Chingola KCM.
- Solnordal, C. B., Jorgensen, R. A., Koh, P. L., & Hunt, A. (2006). *CFD modeling of the flow and reactions in the Olympic Dam flash furnace smelter reaction shaft*.

- Syamujulu, M. (2007). Opportunities, problems and survival strategies from recent developments in the copper concentrate treatment and smelting practices at Vedanta's Konkola Copper mines in the Zambian copperbelt. *The Carlos Diaz symposium of pyrometallurgy*, (pp. 155-166). Montreal, Canada.
- Takeda, Y., Kanesaka, S., Hino, M., & Yazawa, A. (1995). Dissolution of metals in iron oxide slags equilibrating with copper-nickel-iron alloy. *Institution of Mining and Metallurgy*, 285 - 294.
- Taskinen, P. (2009). *KCM Slag training course handouts*. Helsinki University of Technology.
- Taskinen, P., & Kojo, J. (2009). Fluxing options in the direct to blister copper smelting. *Molten 2009*. Santiago, Chile.
- Taskinen, P., Vaarno, J., Jarvi, J., Ahokainen, T., & Laurila, J. (2003). Development of a mathematical model of the flash smelting and converting process. *3rd international conference on CRD in the minerals and process industries, CSIRO*, (pp. 147-154). Melborn, Australia.
- Touminen, J., & Kojo, I. (2005). *Blister flash smelting-efficient and flexible low-cost continuous copper process*. Warrendale, USA.
- Warczok, A., Riveros, G., Marin, T., Degel, R., Kunze, J., Oterdoom, H., & Wuebbels, T. (2007). Intensive electrodynamic slag cleaning. *The Carlos Diaz symposium on pyrometallurgy*, (pp. 403-416).
- White, F. M. (2006). *Viscous fluid flow 3rd edition*. University of Rhode Island.
- Yazawa, A., Takeda, Y., & Nakazawa, S. (1999). Ferrous calcium silicate slag to use for copper smelting. *Copper 99-cobre 99 Final technical Program*, (p. 59).
- Zivkovic, Z., Mitevska, N., Mihajlovic, I., & Nolic, D. (2009). The influence of the silicate slag composition on copper losses during smelting of the sulphide concentrates. *Journal of Mining and Metallurgy B. Metallurgy* 45(1), 21-24.
- Zun-qiu, T. A. (2003). Technical comparison of Pierce-Smith and Flash Copper Converting Process. *Nonferrous Metals*, 2.

# APPENDICES

**APPENDIX A: The Ellingham diagram showing the standard free energy of formation of oxides versus temperature. Equilibrium partial pressure of oxygen and the  $CO/CO_2$  ratio corresponding to the temperature and standard free energy are shown adjacently (Firdu, 2009)**



**APPENDIX B: A calculation framework in an excel-worksheet for calculating the Gibbs free energy change of the dominant reactions in the slag reduction process (Firdu, 2009).**

<p>Reaction: <math>\text{Cu}_2\text{O}(\text{l}) + \text{C} = 2\text{Cu}(\text{l}) + \text{CO}(\text{g})</math></p> $\Delta G_{\text{Cu}} = RT \left( \ln \left( \frac{P_{\text{CO}} (a_{\text{Cu}})^2}{a_{\text{Cu}_2\text{O}}} \right) - \ln(K_p) \right) < 0$ <table border="1"> <tr><td>R</td><td>8.3145 (J · K<sup>-1</sup> · mol<sup>-1</sup>)</td></tr> <tr><td>T (K)</td><td>1573 validity: 1523-1623</td></tr> <tr><td>P<sub>CO</sub></td><td>1</td></tr> <tr><td>a<sub>Cu</sub></td><td>4.55E-01</td></tr> <tr><td>a<sub>CuO0,5</sub></td><td>0.0471875</td></tr> <tr><td>k<sub>p</sub></td><td>3.38E+06 399.2925906</td></tr> <tr><td>P<sub>O2</sub></td><td>6.84399E-14</td></tr> <tr><td>ΔG<sub>r</sub></td><td>-1.77E+05 J/mol</td></tr> </table>	R	8.3145 (J · K <sup>-1</sup> · mol <sup>-1</sup> )	T (K)	1573 validity: 1523-1623	P <sub>CO</sub>	1	a <sub>Cu</sub>	4.55E-01	a <sub>CuO0,5</sub>	0.0471875	k <sub>p</sub>	3.38E+06 399.2925906	P <sub>O2</sub>	6.84399E-14	ΔG <sub>r</sub>	-1.77E+05 J/mol	<p>Reaction: <math>\text{FeO}(\text{l}) + \text{C} = \text{Fe} + \text{CO}</math></p> $\Delta G_{\text{Fe}} = RT \left( \ln \left( \frac{P_{\text{CO}} (a_{\text{Fe}})}{a_{\text{FeO}}} \right) - \ln(K_p) \right) < 0$ <table border="1"> <tr><td>R</td><td>8.3145 (J · K<sup>-1</sup> · mol<sup>-1</sup>)</td></tr> <tr><td>T (K)</td><td>1573</td></tr> <tr><td>P<sub>CO</sub></td><td>1</td></tr> <tr><td>a<sub>Fe</sub></td><td>8.78E-01</td></tr> <tr><td>a<sub>FeO</sub></td><td>0.4</td></tr> <tr><td>k<sub>p</sub></td><td>8.41E+02</td></tr> <tr><td>P<sub>O2</sub></td><td>6.84E-14</td></tr> <tr><td>ΔG<sub>r</sub></td><td>-7.78E+04 J/mol</td></tr> </table>	R	8.3145 (J · K <sup>-1</sup> · mol <sup>-1</sup> )	T (K)	1573	P <sub>CO</sub>	1	a <sub>Fe</sub>	8.78E-01	a <sub>FeO</sub>	0.4	k <sub>p</sub>	8.41E+02	P <sub>O2</sub>	6.84E-14	ΔG <sub>r</sub>	-7.78E+04 J/mol				
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## APPENDIX C1: Mass Balance calculations for the month of January 2016

<b>JANUARY FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	24.09	15.06	14.94	2.56	1.74	1.18	20.33	4.06	1.27
SLAG	20.28	23.14	28.71	4.39	3.15	1.23	0.12	4.57	2.14
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (53.57)	12.38	14.13	17.53	2.68	1.92	0.75	0.07	2.79	1.30
Blister copper	15.88	3.54	-	-	-	0.63	23.78	-	-
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
SLAG	43.81	79.97	100.00	100.00	100.00	54.43	0.31	100.00	100.00
BLISTER Copper	56.19	20.03	-	-	-	45.57	99.69	-	-
<b>JANUARY SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	20.28	23.14	28.71	4.39	3.15	1.23	0.12	4.57	85.61
SCF slag	6.76	27.19	33.43	6.03	4.96	1.05	0.22	9.57	89.21
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(89.49)	6.78	27.28	33.54	6.05	4.97	1.05	0.22	9.60	
BLISTER	16.91	-0.25	-	-	-	0.39	-0.08	-	
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	28.61	100.00	100.00	100.00	100.00	72.96	100.00	100.00	
BLISTER Copper	71.39	-	-	-	-	27.04	-	-	
<b>JANUARY COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	6.76	27.19	33.43	6.03	4.96	1.05	0.22	9.57	89.21
CRF Slag	0.96	28.39	38.60	8.02	5.96	0.61	0.11	9.76	92.41
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(89.71)	0.93	27.56	37.47	7.78	5.79	0.60	0.10	9.48	
Co-Cu Alloy	6.65	2.92	-	-	-	0.58	0.15	-	
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	12.27	90.42	100.00	100.00	100.00	50.64	40.78	100.00	
Co-Cu Alloy	87.73	9.58	-	-	-	49.36	59.22	-	

## APPENDIX C2: Mass Balance calculations for the month of February 2016

<b>FEBRUARY FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	29.20	14.66	14.54	2.20	1.73	0.82	20.41	3.91	1.36
SLAG	20.79	22.15	28.58	4.49	3.22	0.99	0.12	4.60	2.22
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (49.92)	11.91	12.69	16.34	2.57	1.85	0.57	0.07	2.63	1.27
Blister Copper	20.96	3.81	-	-	-	0.35	22.91	-	-
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
SLAG	36.23	76.91	100.00	100.00	100.00	61.82	0.30	100.00	100.00
BLISTER Copper	63.77	23.09	-	-	-	38.18	99.70	-	-
<b>FEBRUARY SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	20.79	22.15	28.58	4.49	3.22	0.99	0.12	4.60	84.95
SCF slag	6.40	24.85	34.63	6.27	5.30	0.91	0.17	10.50	89.03
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(86.49)	6.22	24.14	33.64	6.09	5.15	0.89	0.17	10.20	
BLISTER Copper	18.25	1.93	-	-	-	0.28	-0.03	-	
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	25.41	92.60	100.00	100.00	100.00	75.98	100.00	100.00	
BLISTER Copper	74.59	7.40	-	-	-	24.02	-	-	
<b>FEBRUARY COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	6.40	24.85	34.63	6.27	5.30	0.91	0.17	10.50	89.03
CRF Slag	1.52	25.99	39.31	8.09	6.08	0.68	0.11	9.82	91.61
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(89.71)	1.50	25.72	38.90	8.00	6.02	0.34	0.11	9.72	
Co-Cu Alloy	5.69	2.19	-	-	-	0.68	0.08	-	
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	20.88	92.15	100.00	100.00	100.00	33.44	57.41	100.00	
Co-Cu Alloy	79.12	7.85	-	-	-	66.56	42.59	-	

**APPENDIX C3: Mass balance calculations for the month of March 2016**

<b>MARCH FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	30.67	14.72	13.85	2.02	1.76	0.52	20.89	3.29	1.19
SLAG	20.88	22.20	28.58	4.78	3.13	0.86	0.12	4.42	2.14
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (47.48)	11.38	12.10	15.56	2.60	1.71	0.47	0.07	2.41	1.16
Blister Copper	23.12	4.46	-	-	-	0.11	23.43	1.29	-
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
SLAG	32.99	73.07	100.00	100.00	100.00	81.07	0.28	100.00	100.00
BLISTER Copper	67.01	26.93	-	-	-	18.93	99.72	-	-
<b>MARCH SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	20.88	22.20	28.58	4.78	3.13	0.86	0.12	4.42	84.98
SCF slag	7.33	25.34	33.50	6.41	4.87	0.75	0.24	8.86	87.29
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(87.63)	7.36	25.43	33.63	6.43	4.89	0.76	0.24	8.89	
BLISTER Copper	17.21	0.69	-	-	-	0.25	-	-	
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	29.95	97.36	100.00	100.00	100.00	75.17	100.00	100.00	
BLISTER Copper	70.05	2.64	-	-	-	24.83	-	-	
<b>MARCH COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	7.33	25.34	33.50	6.41	4.87	0.75	0.24	8.86	87.29
CRF Slag	3.08	28.34	36.64	7.93	5.85	0.77	0.14	8.30	91.05
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(95.37)	3.23	29.68	38.38	8.31	6.13	0.05	0.15	8.69	
Co-Cu Alloy	5.17	-0.65	-	-	-	0.81	0.12	-	
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	38.42	100.00	100.00	100.00	100.00	5.84	55.00	100.00	
Co-Cu Alloy	61.58	-	-	-	-	94.16	45.00	-	

**APPENDIX C4: Mass balance calculations for the month of April 2016**

<b>APRIL FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	29.81	14.70	14.00	2.20	1.69	0.40	20.98	3.00	1.06
SLAG	19.61	22.37	27.43	4.80	3.12	0.23	0.11	4.16	2.10
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (48.77)	11.39	13.00	15.94	2.79	1.81	0.13	0.06	2.42	1.22
Blister Copper	22.55	3.73	-	-	-	0.33	23.82	-	-
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
SLAG	33.57	77.70	100.00	100.00	100.00	28.83	0.27	100.00	100.00
BLISTER Copper	66.43	22.30	-	-	-	71.17	99.73	-	-
<b>APRIL SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	19.61	22.37	27.43	4.80	3.12	0.23	0.11	4.16	81.83
SCF slag	7.26	25.00	33.77	6.40	5.58	0.67	0.24	8.08	87.01
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(86.37)	7.21	24.82	33.52	6.35	5.54	0.67	0.24	8.02	
BLISTER Copper	16.75	2.52	-	-	-	-	-	-	
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	30.08	90.78	100.00	100.00	100.00	100.00	100.00	100.00	
BLISTER Copper	69.92	9.22	-	-	-	-	-	-	
<b>APRIL COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	7.26	25.00	33.77	6.40	5.58	0.67	0.24	8.08	
CRF Slag	1.57	27.34	38.32	8.07	6.09	0.19	0.12	8.92	
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(89.71)	1.59	27.69	38.81	8.17	6.17	0.19	0.12	9.03	
Co-Cu Alloy	6.75	1.04	-	-	-	0.58	0.16	-	
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	19.07	96.38	100.00	100.00	100.00	24.77	42.62	100.00	
Co-Cu Alloy	80.93	3.62	-	-	-	75.23	57.38	-	

## APPENDIX C5: Mass balance calculations for the month of May 2016

MAY FLASH SMELTING FURNACE ASSAYS									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
FEED	29.52	14.68	14.15	1.96	1.71	0.62	20.97	3.05	1.19
SLAG	20.17	22.05	28.70	4.38	2.90	1.00	0.12	4.28	2.19
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (48.15)	11.32	12.38	16.11	2.46	1.63	0.56	0.07	2.40	1.23
Blister Copper	22.29	4.33	-	-	-	0.15	23.8	-	-
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
SLAG	33.68	74.08	100.00	100.00	100.00	78.99	0.28	100.00	100.00
BLISTER Copper	66.32	25.92	-	-	-	21.01	99.72	-	-
<b>MAY SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	20.17	22.05	28.70	4.38	2.90	1.00	0.12	4.28	83.59
SCF slag	6.56	25.10	34.08	6.07	5.58	1.04	0.25	8.66	87.33
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(87.98)	6.61	25.28	34.33	6.11	5.62	1.05	0.25	8.72	
BLISTER Copper	17.52	1.1	-	-	-	0.15	-	-	
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	27.40	95.83	100.00	100.00	100.00	87.49	100.00	100.00	
BLISTER Copper	72.60	4.17	-	-	-	12.51	-	-	
<b>MAY COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	6.56	25.10	34.08	6.07	5.58	1.04	0.25	8.66	87.33
CRF Slag	1.21	25.78	39.75	8.15	6.30	0.58	0.12	9.68	91.57
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(89.99)	1.19	25.33	39.02	8.01	6.20	0.57	0.12	9.51	
Co-Cu Alloy	6.32	3.41	-	-	-	0.62		-	
<b>% Splits in streams</b>									
	CU%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	15.81	88.14	100.00	100.00	100.00	47.80		100.00	
Co-Cu Alloy	84.19	11.86	-	-	-	52.20		-	

**APPENDIX C6: Mass balance calculations for the month of June 2016**

<b>JUNE FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
FEED	31.70	14.29	15.43	3.08	1.93	0.44	20.62	3.91	1.20
SLAG	21.17	22.43	31.55	5.52	3.65	0.80	0.09	4.93	2.23
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (48.79)	11.18	11.85	16.66	2.91	1.93	0.42	0.05	2.60	1.18
Blister Copper	23.06	3.58	0	0	0	0.06	22.22	0	0
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
SLAG	32.65	76.80	100.00	100.00	100.00	87.58	0.21	100.00	100.00
BLISTER Copper	67.35	23.2	-	-	-	12.42	99.79	-	-
<b>JUNE SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	21.17	22.43	31.55	5.52	3.65	0.80	0.09	4.93	90.14
SCF slag	6.79	24.60	36.66	7.19	4.86	0.85	0.14	10.88	91.96
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(87.80t)	6.48	23.48	35.00	6.87	4.64	0.81	0.14	10.39	
BLISTER	17.01	1.4	-	-	-	0.08	-0.03	-	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	27.59	94.37	100.00	100.00	100.00	90.99	100.00	100.00	
BLISTER Copper	72.41	5.63	-	-	-	9.01	-	-	
<b>JUNE COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	6.79	24.60	36.66	7.19	4.86	0.85	0.14	10.88	91.96
CRF Slag	1.62	25.16	39.79	7.46	6.11	0.82	0.22	9.56	90.74
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(90.92)	1.62	25.21	39.87	7.48	6.12	0.10	0.22	9.58	
Co-Cu Alloy	5.76	1.54	-	-	-	0.82	0.06	-	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	21.97	94.24	100.00	100.00	100.00	10.87	78.68	100.00	
Co-Cu Alloy	78.21	5.76	-	-	-	89.13	21.32	-	

**APPENDIX C7: Mass balance calculations for the month of July 2016**

<b>JULY FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O
FEED	29.04	13.86	16.48	2.95	1.93	0.37	20.04	4.22	1.24
SLAG	20.15	20.20	30.84	5.78	4.53	0.69	0.07	4.81	2.15
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (52.88)	11.94	11.97	18.28	3.43	2.69	0.41	0.04	2.85	1.27
Blister Copper	20.28	3.41	-	-	-	0	22.19	-	-
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
SLAG	37.06	77.83	100.00	100.00	100.00	100.00	0.20	100.00	100.00
BLISTER Cu/GAS	62.94	22.17	-	-	-	-	99.8	-	-
<b>JULY SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	20.15	20.20	30.84	5.78	4.53	0.69	0.07	4.81	87.07
SCF slag	6.93	24.38	35.77	8.22	6.29	0.74	0.30	10.91	93.55
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(92.63)	6.86	24.14	35.42	8.14	6.23	0.74	0.30	10.80	
BLISTER Copper	16.31	-0.94	-	-	-	0.05	-0.22	0	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	29.62	100.00	100.00	100.00	100.00	93.64	100.00	100.00	
BLISTER Copper	70.38	-	-	-	-	6.36	-	-	
<b>JULY COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	6.93	24.38	35.77	8.22	6.29	0.74	0.30	10.91	93.55
CRF Slag	1.54	23.56	41.12	8.01	6.78	0.35	0.27	10.01	91.65
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(85.23)	1.43	21.91	38.24	7.45	6.30	0.33	0.25	9.31	
Co-Cu Alloy	6.00	4.15	-	-	-	0.46	0.07	-	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	19.26	84.08	100.00	100.00	100.00	41.61	78.29	100.00	
Co-Cu Alloy	80.74	15.92	-	-	-	58.39	21.71	-	

## APPENDIX C8: Mass balance calculations for the month of August 2016

	AUGUST FLASH SMELTING FURNACE ASSAYS								
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O
FEED	31.03	12.73	16.82	2.48	1.89	0.43	19.73	3.94	1.14
SLAG	20.03	17.53	31.46	5.11	4.16	0.71	0.08	4.58	2.07
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (50.81)	11.87	10.39	18.65	3.03	2.47	0.42	0.05	2.71	1.23
Blister Copper	22.54	3.72	-	-	-	0.06	21.83	-	-
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
SLAG	34.50	73.63	100.00	100.00	100.00	87.52	0.22	100.00	100.00
BLISTER Copper	65.5	96.28	-	-	-	12.48	99.78	-	-
<b>AUGUST SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	20.03	17.53	31.46	5.11	4.16	0.71	0.08	4.58	83.64
SCF slag	7.26	20.05	37.18	6.92	5.27	0.80	0.17	9.97	87.61
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(88.63)	7.34	20.28	37.61	7.00	5.33	0.81	0.17	10.08	
BLISTER Copper	16.61	0.68	-	-	-	0.04	0.03	-	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	30.65	96.76	100.00	100.00	100.00	95.27	85.29	100.00	
BLISTER Copper	69.35	3.24	-	-	-	4.73	14.71	-	
<b>AUGUST COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	7.26	20.05	37.18	6.92	5.27	0.80	0.17	9.97	87.61
CRF Slag	1.81	21.18	44.36	8.72	7.01	0.31	0.17	9.87	93.43
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(89.38)	1.73	20.26	42.44	8.35	6.71	0.29	0.17	9.44	
Co-Cu Alloy	6.56	2.63	-	-	-	0.62	0.02	-	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	20.89	88.51	100.00	100.00	100.00	32.05	89.24	100.00	
Co-Cu Alloy	79.11	11.49	-	-	-	67.95	10.74	-	

**APPENDIX C9: Mass balance calculations for the month of January 2015**

<b>JANUARY FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	26.48	13.76	17.79	2.23	2.24	0.56	19.48	3.33	1.88
SLAG	19.73	23.05	31.84	4.62	4.29	0.91	0.10	4.00	2.01
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS=100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (57.64)	12.56	14.67	20.27	2.94	2.73	0.58	0.06	2.54	1.28
Blister Copper	17.62	1.01	-	-	-	0.06	22.14	-	-
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
SLAG	41.62	93.56	100.00	100.00	100.00	90.60	0.29	100.00	100.00
BLISTER Copper	58.38	6.44	-	-	-	9.40	99.71	-	-
<b>JANUARY SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	19.73	23.05	31.84	4.62	4.29	0.91	0.10	4.00	88.53
SCF slag	6.12	23.18	36.10	6.45	4.91	0.95	0.06	6.74	84.51
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS=100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(84.19)	6.10	23.09	35.97	6.42	4.89	0.94	0.06	6.72	
BLISTER Copper	16.19	2.95	-	-	-	0.08	0.05	-	
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	27.35	88.68	100.00	100.00	100.00	92.19	55.76	100.00	
BLISTER Copper	72.65	11.32	-	-	-	7.81	44.24	-	
<b>JANUARY COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	6.12	23.18	36.10	6.45	4.91	0.95	0.06	6.74	84.51
CRF Slag	1.30	24.39	39.96	7.82	5.41	0.54	0.19	8.34	87.96
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS=100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(94.03)	1.39	26.07	42.72	8.36	5.79	0.55	0.21	8.91	
Co-Cu Alloy	5.85	1.36	-	-	-	0.58	-	-	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	19.21	95.04	100.00	100.00	100.00	48.33	-	100.00	
Co-Cu Alloy	80.79	4.96				51.67	-		

**APPENDIX C10: Mass balance calculations for the month of February 2015**

<b>FEBRUARY FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	27.37	14.00	17.64	1.73	1.86	0.75	22.70	3.69	1.27
SLAG	19.32	22.64	31.46	3.26	2.96	1.15	0.12	4.15	2.17
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (53.74)	11.90	13.95	19.38	2.01	1.82	0.71	0.07	2.56	1.34
Blister Copper	18.17	1.43	-	-	-	0.11	24.87	-	-
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
SLAG	39.57	90.70	100.00	100.00	100.00	86.17	0.30	100.00	100.00
BLISTER Copper	60.43	9.30	-	-	-	13.83	99.70	-	-
<b>FEBRUARY SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	19.32	22.64	31.46	3.26	2.96	1.15	0.12	4.15	85.06
SCF slag	6.62	22.80	36.73	5.11	3.52	1.08	0.07	7.55	83.49
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(84.07)	6.67	22.96	36.99	5.14	3.55	1.09	0.07	7.61	
BLISTER Copper	16.05	3.66	-	-	-	0.26	0.07	-	
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	29.35	86.25	100.00	100.00	100.00	80.75	47.27	100.00	
BLISTER Copper	70.65	13.75	-	-	-	19.25	52.73	-	
<b>FEBRUARY COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	6.62	22.80	36.73	5.11	3.52	1.08	0.07	7.55	83.49
CRF Slag	1.55	24.93	40.99	7.10	3.89	0.71	0.21	8.61	87.98
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(94.43)	1.66	26.75	43.99	7.62	4.18	0.53	0.23	9.24	
Co-Cu Alloy	6.27	0.56	-	-	-	0.76	-	-	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	20.93	97.95	100.00	100.00	100.00	41.09	-	100.00	
Co-Cu Alloy	79.07	2.05	-	-	-	58.91	-	-	

**APPENDIX C11: Mass balance calculations for the month of March 2015**

<b>MARCH FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	26.36	13.84	17.71	1.98	1.71	0.85	19.93	3.80	1.32
SLAG	19.24	23.52	31.70	3.83	2.72	1.41	0.10	4.41	2.18
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (56.90)	12.29	15.02	20.24	2.44	1.74	0.90	0.07	2.81	1.39
Blister Copper	17.84	0.80	-	-	-	0.07	22.71	-	-
<b>% Split in streams</b>									
SLAG	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
BLISTER Copper	40.79	94.94	100.00	100.00	100.00	92.78	0.29	100.00	100.00
	59.21	5.06	-	-	-	7.22	99.71	-	-
<b>MARCH SLAG CLEANING FURNACE ASSAYS</b>									
FSF slag feed	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF slag	19.24	23.52	31.70	3.83	2.72	1.41	0.10	4.41	86.93
	6.53	23.26	35.99	5.17	3.12	1.28	0.08	8.10	83.53
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(84.64)	6.62	23.57	36.47	5.24	3.17	1.29	0.08	8.21	
BLISTER Copper	15.52	3.49	-	-	-	0.33	0.03	-	
<b>% Split in streams</b>									
SLAG	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
BLISTER Copper	29.89	87.10	100.00	100.00	100.00	79.67	73.07	100.00	
	70.11	12.90	-	-	-	20.33	26.93	-	
<b>MARCH COBALT RECOVERY FURNACE ASSAYS</b>									
SCF Slag feed	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
CRF Slag	6.53	23.26	35.99	5.17	3.12	1.28	0.08	8.10	83.53
	1.35	25.08	39.39	7.21	3.30	0.87	0.21	8.88	86.27
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(94.37)	1.47	27.43	43.09	7.88	3.61	0.58	0.23	9.71	
Co-Cu Alloy	6.34	0.42	-	-	-	0.95	-	-	
<b>% Splits in streams</b>									
SLAG	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
Co-Cu Alloy	18.85	98.49	100.00	100.00	100.00	37.91	-	100.00	
	81.15	1.51	-	-	-	62.09	-	-	

**APPENDIX C12: Mass balance calculations for the month of April 2015**

<b>APRIL FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	25.67	14.10	17.71	2.17	2.72	0.78	19.62	3.77	1.30
SLAG	19.46	24.51	31.51	3.78	3.24	1.11	0.11	4.32	2.11
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (57.69)	12.45	15.68	20.16	2.42	2.07	0.71	0.07	2.77	1.35
Blister Copper	16.78	0.37	-	-	-	0.18	22.27	-	-
<b>% Split in streams</b>									
SLAG	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
Blister Copper	42.60	97.70	100.00	100.00	100.00	79.76	0.33	100.00	100.00
	57.40	2.30	-	-	-	20.24	99.67	-	-
<b>APRIL SLAG CLEANING FURNACE ASSAYS</b>									
FSF slag feed	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF slag	19.46	24.51	31.51	3.78	3.24	1.11	0.11	4.32	88.03
	6.53	23.97	35.43	5.45	3.69	1.01	0.11	7.75	83.93
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(84.79)	6.60	24.21	35.79	5.50	3.73	1.02	0.11	7.82	
Blister Copper	15.51	3.63	-	-	-	0.16	0.01	-	
<b>% Split in streams</b>									
SLAG	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
Blister Copper	29.84	86.96	100.00	100.00	100.00	86.44	91.92	100.00	
	70.16	13.04	-	-	-	13.56	8.08	-	
<b>APRIL COBALT RECOVERY FURNACE ASSAYS</b>									
SCF Slag feed	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
CRF Slag	6.53	23.97	35.43	5.45	3.69	1.01	0.11	7.75	83.93
	1.20	25.68	38.89	7.24	3.94	0.62	0.22	8.72	86.50
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(93.89)	1.30	27.87	42.21	7.86	4.28	0.53	0.23	9.46	
Co-Cu Alloy	6.48	0.69	-	-	-	0.67	-	-	
<b>% Splits in streams</b>									
SLAG	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
Co-Cu Alloy	16.71	97.58	100.00	100.00	100.00	44.17	-	100.00	
	83.29	2.42	-	-	-	55.83	-	-	

**APPENDIX C13: Mass balance calculations for the month of May 2015**

<b>MAY FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	25.67	14.51	16.62	2.77	1.90	0.89	20.07	4.13	1.43
SLAG	19.31	21.91	31.88	3.87	2.99	1.18	0.12	4.57	2.26
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (52.19)	11.44	12.98	18.89	2.29	1.77	0.70	0.07	2.71	1.34
Blister Copper	17.73	3.51	-	-	-	0.31	22.73	-	-
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
SLAG	39.21	78.71	100.00	100.00	100.00	69.30	0.32	100.00	100.00
Blister Copper	60.79	21.29	-	-	-	30.70	99.68	-	-
<b>MAY SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	19.31	21.91	31.88	3.87	2.99	1.18	0.12	4.57	85.84
SCF slag	6.51	22.26	36.35	5.60	3.42	1.09	0.10	8.84	84.17
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(86.00)	6.65	22.74	37.14	5.72	3.49	1.12	0.10	9.04	
Blister Copper	15.84	2.78	-	-	-	0.26	0.04	-	
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	29.58	89.11	100.00	100.00	100.00	81.12	71.38	100.00	
Blister Copper	70.42	10.89	-	-	-	18.88	28.62	-	
<b>MAY COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	6.51	22.26	36.35	5.60	3.42	1.09	0.10	8.84	84.17
CRF Slag	1.41	23.69	40.82	7.37	3.86	0.58	0.24	9.30	87.28
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(92.29)	1.50	25.05	43.19	7.80	4.09	0.61	0.26	9.83	
Co-Cu Alloy	6.24	1.40	-	-	-	0.69	-	-	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	19.33	94.71	100]	100.00	100.00	46.89	-	100.00	
Co-Cu Alloy	80.67	5.29	-	-	-	53.11	-	-	

**APPENDIX C14: Mass balance calculations for the month of June 2015**

<b>JUNE FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	23.42	15.72	16.71	3.24	2.23	1.80	20.79	4.13	1.40
SLAG	19.48	25.34	33.11	4.57	3.21	1.23	0.12	4.69	2.20
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (53.01)	10.99	14.30	18.68	2.58	1.81	0.69	0.07	2.64	1.24
Blister Copper	15.20	3.28	-	-	-	1.32	23.18	-	-
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
SLAG	41.96	81.34	100.00	100.00	100.00	34.49	0.29	100.00	100.00
Blister Copper	58.04	18.66	-	-	-	65.51	99.71	-	-
<b>JUNE SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	19.48	25.34	33.11	4.57	3.21	1.23	0.12	4.69	91.75
SCF slag	6.17	24.12	36.66	6.12	3.53	1.13	0.10	8.50	86.33
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(84.98)	6.07	23.74	36.09	6.03	3.48	1.11	0.10	8.37	
Blister Copper	15.16	3.87	-	-	-	0.23	0.04	-	
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	28.60	85.99	100.00	100.00	100.00	82.81	70.43	100.00	
Blister Copper	71.40	14.01	-	-	-	17.19	29.57	-	
<b>JUNE COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	6.17	24.12	36.66	6.12	3.53	1.13	0.10	8.50	86.33
CRF Slag	0.43	24.99	40.54	7.70	3.99	0.46	0.28	8.93	87.32
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(91.47)	0.46	26.18	42.46	8.07	4.18	0.48	0.30	9.35	
Co-Cu Alloy	6.69	1.76	-	-	-	0.83	-	-	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	6.37	93.70	100.00	100.00	100.00	36.69	-	100.00	
Co-Cu Alloy	93.63	6.30	-	-	-	63.31	-	-	

**APPENDIX C15: Mass balance calculations for the month of July 2015**

<b>JULY FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	25.03	15.25	16.71	2.78	2.29	1.52	20.54	4.54	1.51
SLAG	19.38	24.99	32.69	4.60	2.78	1.58	0.10	4.85	2.23
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (52.82)	10.98	14.16	18.53	2.61	1.57	0.89	0.06	2.75	1.26
Blister Copper	16.77	2.75	-	-	-	0.79	22.72	-	-
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
SLAG	39.57	83.74	100.00	100.00	100.00	53.10	0.26	100.00	100.00
Blister Copper	60.43	16.26	-	-	-	46.90	99.74	-	-
<b>JULY SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	19.38	24.99	32.69	4.60	2.78	1.58	0.10	4.85	90.96
SCF slag	6.42	23.67	35.94	6.16	3.02	1.34	0.10	8.82	85.46
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(85.46)	6.42	23.67	35.94	6.16	3.02	1.34	0.10	8.82	
Blister Copper	14.49	3.80	-	-	-	0.40	0.01	-	
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	30.71	86.17	100.00	100.00	100.00	76.97	90.52	100.00	
Blister Copper	69.29	13.83	-	-	-	23.03	9.48	-	
<b>JULY COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	6.42	23.67	35.94	6.16	3.02	1.34	0.10	8.82	85.46
CRF Slag	1.39	25.03	38.91	7.58	3.20	0.92	0.25	9.15	86.41
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(93.39)	1.50	27.05	42.05	8.19	3.46	0.57	0.27	9.94	
Co-Cu Alloy	6.02	0.65	-	-	-	1.00	-	-	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	19.91	97.65	100.00	100.00	100.00	36.31	-	100.00	
Co-Cu Alloy	80.09	2.35	-	-	-	63.69	-	-	

**APPENDIX C16: Mass balance calculations for the month of August 2015**

<b>AUGUST FLASH SMELTING FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O%
FEED	25.41	15.69	15.81	2.59	2.22	1.34	20.69	4.38	2.21
SLAG	19.26	25.47	32.20	4.66	3.05	1.47	0.11	5.01	2.21
<b>FSF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O
Slag (50.79)	10.47	13.84	17.50	2.53	1.66	0.80	0.06	2.73	1.20
Blister Copper	17.66	3.52	-	-	-	0.69	22.85	-	-
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %
SLAG	37.21	79.73	100.00	100.00	100.00	53.63	0.26	100.00	100.00
Blister Copper	62.79	20.27	-	-	-	46.37	99.74	-	-
<b>AUGUST SLAG CLEANING FURNACE ASSAYS</b>									
	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
FSF slag feed	19.26	25.47	32.20	4.66	3.05	1.47	0.11	5.01	91.23
SCF slag	7.15	23.09	35.24	6.11	3.33	1.26	0.09	9.13	85.41
<b>SCF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(85.54)	7.16	23.12	35.30	6.12	3.33	1.27	0.09	9.14	
Blister Copper	13.95	4.80	-	-	-	0.35	0.03	-	
<b>% Split in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	33.92	82.81	100.00	100.00	100.00	78.34	75.92	100.00	
Blister Copper	66.08	17.19	-	-	-	21.66	24.08	-	
<b>AUGUST COBALT RECOVERY FURNACE ASSAYS</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SCF Slag feed	7.15	23.09	35.24	6.11	3.33	1.26	0.09	9.13	85.41
CRF Slag	1.18	25.28	37.52	7.60	3.45	0.86	0.21	9.46	85.58
<b>CRF MASS BALANCE</b>									
<b>CALCULATION BASIS = 100 tonnes</b>									
Tonnage	Cu	Fe	SiO <sub>2</sub>	CaO	MgO	Co	S	Al <sub>2</sub> O <sub>3</sub>	
SLAG(94.11)	1.30	27.80	41.26	8.36	3.79	0.52	0.23	10.41	
Co-Cu Alloy	7.07	0.00	-	-	-	0.95	-	-	
<b>% Splits in streams</b>									
	Cu%	Fe%	SiO <sub>2</sub> %	CaO%	MgO%	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	
SLAG	15.51	100.00	100.00	100.00	100.00	35.37	-	100.00	
Co-Cu Alloy	84.49	-	-	-	-	64.63	-	-	

**APPENDIX D.1: Distribution of Cu and Co in various streams (Jan – Aug 2016)**

<b>% Distribution of Cu in FSF Operations 2016</b>								
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Blister	56.19	63.77	67.01	66.43	66.32	67.35	62.94	65.5
Cu in Slag	43.81	36.23	32.99	33.57	33.68	32.65	37.06	34.5
<b>% Distribution of Co in FSF Operations 2016</b>								
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Co in Blister	45.57	38.18	18.93	71.17	21.01	12.42	0	12.48
Co in Slag	54.43	61.82	81.07	28.83	78.99	87.58	100	87.52
<b>% Distribution of Cu in SCF Operations 2016</b>								
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Blister	71.39	74.59	70.05	69.92	72.6	72.41	70.38	69.35
Cu in Slag	28.61	25.41	29.95	30.08	27.4	27.59	29.38	30.65
<b>% Distribution of Co in SCF Operations 2016</b>								
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Co in Blister	27.04	24.02	24.83	0	12.51	9.01	6.36	14.71
Co in Slag	72.96	75.98	75.17	100	87.49	90.99	93.64	85.29
<b>% Distribution of Cu in CRF Operations 2016</b>								
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Cu in Alloy	87.73	79.12	61.58	80.93	84.19	78.21	80.74	79.11
Cu in Slag	12.27	20.88	38.42	19.07	15.81	21.97	19.26	20.89
<b>% Distribution of Co in CRF Operations 2016</b>								
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Co in Alloy	50.64	66.56	94.16	57.38	52.20	89.13	58.39	67.95
Co in Slag	49.36	33.44	5.84	42.62	47.80	10.87	41.61	32.05

**APPENDIX D.2: Distribution of Cu and Co in various streams (Jan – Aug 2015)**

		<b>% Distribution of Cu in FSF Operations 2015</b>							
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Blister		53.38	60.43	59.21	57.4	60.79	58.04	60.43	62.79
Cu in Slag		41.62	39.57	40.79	42.6	39.21	41.96	39.57	37.21
		<b>% Distribution of Co in FSF Operations 2015</b>							
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Co in Blister		9.4	13.83	7.22	20.24	30.7	65.51	46.9	46.37
Co in Slag		90.6	86.17	92.78	79.76	69.3	34.49	53.1	53.63
		<b>% Distribution of Cu in SCF Operations 2015</b>							
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Blister		72.65	70.65	70.11	70.16	70.42	71.4	69.29	66.08
Cu in Slag		27.35	29.35	29.89	29.84	29.58	28.6	30.71	33.92
		<b>% Distribution of Co in SCF Operations 2015</b>							
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Co in Blister		7.81	19.25	20.33	13.56	18.88	17.19	23.03	21.66
Co in Slag		92.19	80.75	79.67	86.44	81.12	82.81	76.97	78.34
		<b>% Distribution of Cu in CRF Operations 2015</b>							
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Cu in Alloy		80.79	79.07	81.15	83.29	80.67	93.63	80.09	84.49
Cu in Slag		19.21	20.93	18.85	16.71	19.33	6.37	19.91	15.51
		<b>% Distribution of Co in CRF Operations 2015</b>							
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Co in Alloy		51.67	58.91	62.09	55.83	53.11	63.31	63.39	64.63
Co in Slag		48.33	41.09	37.91	44.17	46.89	36.69	36.31	35.37

**APPENDIX D.3: Fe, S and O in FSF and SCF blister, Partitioning of Co-in FSF and SCF blister and slag products**

	<b>FSF Blister Quality</b>						
	Jan	Feb	Mar	Apr	May	Jun	Jul
Fe ppm	234.67	215.54	169.71	258.10	73.13	113.14	488.00
O <sub>2</sub> ppm	3209.44	4035.83	3646.63	3497.76	3694.60	3782.28	4102.00
S ppm	1489.11	923.22	1561.75	2130.71	2221.40	2114.44	2222.00
% Cu in Slag	43.81	36.23	32.99	33.57	33.68	32.65	37.06
	<b>SCF Blister Quality</b>						
	Jan	Feb	Mar	Apr	May	Jun	Jul
Fe ppm	571.81	196.93	332.54	89.08	744.73	487.92	253.47
O <sub>2</sub> ppm	415.00	156.29	230.77	399.77	440.55	650.17	634.53
S ppm	2579.00	2960.00	2942.92	2598.38	3175.18	3146.50	3186.53
% feed Cu in Slag	28.61	25.41	29.95	30.08	27.4	27.59	29.62
	<b>Co in SCF Blister</b>						
	Jan	Feb	March	April	May	Jun	Jul
Co in blister (ppm)	1233	2541	911	631	836	1562	852
Co ppm max	1800	1800	1800	1800	1800	1800	1800
	<b>Co Partitioning in FSF</b>						
	Jan	Feb	March	April	May	Jun	July
%Co in slag	1.23	0.99	0.86	0.23	1.00	0.80	0.69
%Co in blister	0.01	0.01	0.01	0.02	0.01	0.01	0.01
Lco	123.00	99.00	86.00	11.50	100.00	80.00	69.00
	<b>Co Partitioning in SCF</b>						
	Jan	Feb	March	April	May	Jun	July
%Co in slag	1.05	0.90	0.75	0.67	1.04	0.85	0.74
%Co in blister	0.12	0.25	0.09	0.06	0.08	0.16	0.09
Lco	8.75	3.60	8.33	11.17	13.00	5.31	8.22
	<b>FSF and SCF Lcos</b>						
	Jan	Feb	March	April	May	Jun	July
FSF Lco	123.00	99.00	86.00	11.50	100.00	80.00	69.00
SCF Lco	8.75	3.60	8.33	11.17	13.00	5.31	8.22

**APPENDIX E1: Feed blend, slag assays, blister assays and ASCu data for FSF operations (2016)**

FSF Feed Blend 2016													
	Sample IDN	Cu %	fe %	SiO2 %	CaO %	MgO %	Co %	S %	Al2O3 %	K2O %	Bi (ppm)	Fe/SiO2	
Jan	FEED	24.09	15.06	14.94	2.56	1.74	1.18	20.33	4.06	1.27	161.63	1.01	
Feb	FEED	29.20	14.66	14.54	2.20	1.73	0.82	20.41	3.91	1.36	168.07	1.01	
Mar	FEED	30.67	14.72	13.85	2.02	1.76	0.52	20.89	3.29	1.19	172.60	1.07	
Apr	FEED	29.81	14.70	14.00	2.20	1.69	0.40	20.98	3.00	1.06	140.75	1.05	
May	FEED	29.62	14.68	13.89	2.13	1.72	0.57	21.08	2.92	2.30	118.33	1.06	
Jun	FEED	31.73	14.28	15.43	3.07	1.93	0.44	20.63	3.91	1.20	141.07	0.90	
Jul	FEED	29.08	13.84	16.17	3.24	1.91	0.37	20.19	4.15	1.25	125.16	0.86	
Aug	FEED	31.03	12.73	16.82	2.48	1.89	0.43	19.73	3.94	1.14	102.00	0.76	
FSF SLAG ANALYSES 2016													
	Sample IDN	Cu %	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O	Fe <sub>3</sub> O <sub>4</sub> %	Total %	Fe/SiO2
Jan	FSF LAUNDER	20.28	23.14	28.71	4.39	3.15	1.23	0.12	4.57	2.14	27.59	87.74	0.81
Feb	FSF LAUNDER	20.79	22.15	28.58	4.49	3.22	0.99	0.12	4.60	2.22	25.49	87.17	0.78
Mar	FSF LAUNDER	20.88	22.20	28.58	4.78	3.13	0.86	0.12	4.42	2.14	26.44	87.12	0.78
Apr	FSF LAUNDER	19.60	21.63	27.00	4.85	3.21	0.23	0.10	4.02	2.12	27.20	82.74	0.80
May	FSF LAUNDER	20.07	22.30	28.26	4.30	3.02	1.00	0.11	4.21	2.18	28.73	85.46	0.79
Jun	FSF LAUNDER	21.17	22.43	31.55	5.52	3.65	0.80	0.09	4.93	2.23	27.41	92.23	0.71
Jul	FSF LAUNDER	20.15	20.20	30.84	5.78	4.53	0.69	0.07	4.81	2.15	25.84	89.21	0.66
Aug	FSF LAUNDER	20.03	17.53	31.46	5.11	4.16	0.71	0.08	4.58	2.07	21.35	85.71	0.56
FSF Blister Anode 2016													
	Cu %	Fe ppm	Ni ppm	As ppm	Bi ppm	Co ppm	O <sub>2</sub> ppm	S ppm					
	99.20 min	725 max	N/A	1700 max	NA	69 max	5000 max	3000 max					
Jan	99.39	234.67	32.94	482.28	492.56	114.00	3209.44	1489.11					
Feb	99.41	215.54	84.11	208.17	334.28	124.39	4035.83	923.22					
Mar	99.37	169.71	80.50	303.69	386.06	129.63	3646.63	1561.75					
Apr	99.33	258.10	59.19	257.43	316.95	170.19	3497.76	2130.71					
May	99.34	73.13	49.33	297.27	146.53	123.20	3694.60	2221.40					
Jun	99.31	113.14	60.06	376.83	260.67	146.44	3782.28	2114.44					
Jul	99.35	138.21	51.50	222.21	191.50	133.21	4168.64	1608.21					
Aug	99.45	84.75	107.50	253.90	128.85	159.90	3708.95	1087.80					
ASCu in FSF Feed Blend 2016													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug					
% ASCu	1.49	2.14	2.8	2.74	3.34	3.19	2.37	4.08					

**APPENDIX E2: Blister and slag analyses data for SCF and CRF operations (2016)**

SCF SLAG ANALYSES 2016												
	SAMPLE IDN	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	Fe <sub>3</sub> O <sub>4</sub> %	Total %	Fe/SiO <sub>2</sub>
Jan	SCF LAUNDER	6.76	27.19	33.43	6.03	4.96	1.05	0.22	9.57	15.85	89.33	0.86
Feb	SCF LAUNDER	6.40	24.85	34.63	6.27	5.30	0.91	0.17	10.50	14.28	88.95	0.72
Mar	SCF LAUNDER	7.33	25.34	33.50	6.41	4.87	0.75	0.24	8.86	15.22	87.19	0.76
Apr	SCF LAUNDER	7.26	25.00	33.77	6.40	5.58	0.67	0.24	8.08	15.69	86.94	0.74
May	SCF LAUNDER	6.56	25.10	34.08	6.07	5.58	1.04	0.25	8.66	14.05	87.24	0.74
Jun	SCF LAUNDER	6.79	24.60	36.66	7.19	4.86	0.85	0.14	10.88	14.24	90.90	0.67
Jul	SCF LAUNDER	6.93	24.38	35.77	8.22	6.29	0.74	0.30	10.91	14.41	93.48	0.69
Aug	SCF LAUNDER	7.26	20.05	37.18	6.92	5.27	0.80	0.17	9.97	14.29	87.48	0.54
SCF Blister Anode 2016												
	Cu %	Fe ppm	As ppm	Bi ppm	Se ppm	Ni ppm	Co ppm	O <sub>2</sub> ppm	S ppm			
	98.70min	1000max	NA	NA	NA	NA	1800 max	NA	2500 max			
Jan	99.29	571.81	934.88	1038.06	1.00	283.69	1232.63	415.00	2579.00			
Feb	99.21	196.93	647.29	993.00	1.00	427.14	2540.93	156.29	2960.00			
Mar	99.36	332.54	651.00	902.38	1.00	454.38	911.08	230.77	2942.92			
Apr	99.49	89.08	440.62	517.54	1.00	394.85	630.92	399.77	2598.38			
May	99.35	744.73	600.55	280.82	1.00	432.91	835.82	440.55	3175.18			
Jun	99.22	487.92	835.75	437.75	1.00	716.33	1561.92	650.17	3146.50			
Jul	99.34	253.47	570.20	419.53	1.00	662.60	852.20	634.53	3186.53			
Aug	98.96	1766.96	700.70	317.91	1.00	1068.43	2593.17	723.26	3271.70			
CRF Slag Analyses 2016												
	Cu%	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	Fe <sub>3</sub> O <sub>4</sub> %	Total %	Fe/SiO <sub>2</sub>	
Jan	0.56	29.27	38.33	7.76	5.93	0.45	0.11	9.77	1.32	92.17	0.77	
Feb	1.52	25.99	39.31	8.09	6.08	0.68	0.11	9.82	2.28	91.16	0.72	
Mar	3.08	28.34	36.64	7.93	5.85	0.77	0.14	8.30	4.20	91.05	0.77	
Apr	1.57	27.34	38.32	8.07	6.09	0.19	0.12	8.92	2.49	90.60	0.72	
May	1.21	25.78	39.75	8.15	6.30	0.58	0.12	9.68	1.83	90.67	0.65	
Jun	1.62	25.16	39.79	7.46	6.11	0.82	0.22	9.56	2.03	90.74	0.64	
Jul	1.54	23.56	41.12	8.01	6.78	0.35	0.27	10.01	2.22	92.32	0.56	
Aug	1.81	21.18	44.36	8.72	7.01	0.31	0.17	9.87	2.53	93.43	0.48	

**APPENDIX E3: Feed blend, slag assays, blister assays and ASCu data for FSF operations (2015)**

FSF Feed Blend 2015													
	Sample IDN	Cu %	fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O %			
Jan	FEED	26.48	13.76	17.79	2.23	2.24	0.56	19.48	3.33	1.88			
Feb	FEED	27.37	14.00	17.64	1.73	1.86	0.75	22.70	3.69	1.27			
Mar	FEED	26.36	13.84	17.71	1.98	1.71	0.85	19.93	3.80	1.32			
Apr	FEED	25.67	14.10	17.71	2.17	2.72	0.78	19.62	3.77	1.30			
May	FEED	25.67	14.51	16.62	2.77	1.90	0.89	20.07	4.13	1.43			
Jun	FEED	23.42	15.72	16.71	3.24	2.23	1.80	20.79	4.13	1.40			
Jul	FEED	25.03	15.25	16.71	2.78	2.29	1.52	20.54	4.54	1.51			
Aug	FEED	25.41	15.69	15.81	2.59	2.22	1.34	20.69	4.38	2.21			
FSF SLAG ANALYSES 2016													
	Sample IDN	Cu %	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	K <sub>2</sub> O	Fe <sub>3</sub> O <sub>4</sub> %	Total %	Fe/SiO <sub>2</sub>
Jan	FSF LAUNDER	19.73	23.05	31.84	4.62	4.29	0.91	0.10	4.00	2.01	30.20	88.06	0.69
Feb	FSF LAUNDER	19.32	22.64	31.46	3.26	2.96	1.15	0.12	4.15	2.17	32.14	87.09	0.72
Mar	FSF LAUNDER	19.24	23.52	31.70	3.83	2.72	1.41	0.10	4.41	2.18	31.24	89.11	0.79
Apr	FSF LAUNDER	19.46	24.51	31.51	3.78	3.24	1.11	0.11	4.32	2.11	29.85	90.15	0.77
May	FSF LAUNDER	19.31	21.91	31.88	3.87	2.99	1.18	0.12	4.57	2.26	29.36	88.10	0.65
Jun	FSF LAUNDER	19.48	25.34	33.11	4.57	3.21	1.23	0.12	4.69	2.20	32.18	93.95	0.77
Jul	FSF LAUNDER	19.21	25.14	32.22	4.51	2.73	1.59	0.07	4.77	2.23	31.81	92.46	0.78
Aug	FSF LAUNDER	19.26	25.47	32.20	4.66	3.05	1.47	0.11	5.01	2.21	31.92	93.42	0.80
FSF Blister Anode 2015													
	Cu %	Fe ppm	Ni ppm	As ppm	Bi ppm	Co ppm	O <sub>2</sub> ppm	S ppm					
	99.20 min	725 max	N/A	1700 max	NA	69 max	5000 max	3000 max					
Jan	99.51	82.06	139.20	224.03	151.06	133.10	4000.80	966.08					
Feb	99.57	113.25	154.95	355.59	161.26	139.00	3223.36	939.62					
Mar	99.58	96.99	229.23	162.17	167.50	157.02	2940.17	1357.76					
Apr	99.58	68.64	180.27	174.45	162.36	159.73	3015.55	2178.25					
May	99.55	127.79	124.76	369.10	152.43	146.90	3379.57	1269.09					
Jun	99.37	135.34	31.80	322.05	247.64	55.73	3495.85	1952.95					
Jul	99.38	136.94	249.10	174.90	316.00	188.80	3164.80	1999.70					
Aug	99.38	100.32	186.16	164.88	313.56	209.72	3321.64	1948.56					
ASCu in FSF Feed Blend 2015													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug					
% ASCu	0.97	0.92	0.96	0.84	0.87	0.69	0.87	0.94					

**APPENDIX E4: Blister and slag analyses data for SCF and CRF operations (2015)**

SCF SLAG ANALYSES 2015												
	SAMPLE IDN	Cu %	Fe %	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	Fe <sub>3</sub> O <sub>4</sub> %	Total %	Fe/SiO <sub>2</sub>
Jan	SCF LAUNDER	6.12	23.18	36.10	6.45	4.91	0.95	0.06	6.74	13.26	82.39	0.53
Feb	SCF LAUNDER	6.62	22.80	36.73	5.11	3.52	1.08	0.07	7.55	15.26	83.48	0.59
Mar	SCF LAUNDER	6.53	23.26	35.99	5.17	3.12	1.28	0.08	8.10	14.62	83.66	0.60
Apr	SCF LAUNDER	6.53	23.97	35.43	5.45	3.69	1.01	0.11	7.75	15.33	83.93	0.68
May	SCF LAUNDER	6.51	22.26	36.35	5.60	3.42	1.09	0.10	8.84	14.33	84.17	0.61
Jun	SCF LAUNDER	6.17	24.12	36.66	6.12	3.53	1.13	0.10	8.50	13.51	86.31	0.66
Jul	SCF LAUNDER	6.42	23.67	35.94	6.16	3.02	1.34	0.10	8.82	14.00	85.45	0.66
Aug	SCF LAUNDER	7.15	23.09	35.24	6.11	3.33	1.26	0.09	9.13	16.32	85.40	0.66
SCF Blister Anode 2015												
	Cu %	Fe ppm	As ppm	Bi ppm	Se ppm	Ni ppm	Co ppm	O <sub>2</sub> ppm	S ppm			
	98.70min	1000max	NA	NA	NA	NA	1800 max	NA	2500 max			
Jan	99.07	1111.96	558.78	287.36	32.44	1014.63	2481.64	653.88	3181.39			
Feb	99.17	834.56	662.22	288.03	12.78	1028.67	2460.33	262.03	2733.61			
Mar	98.95	467.08	394.33	315.94	50.44	1312.54	2607.55	305.33	3648.17			
Apr	99.20	668.28	291.38	319.75	50.38	1079.38	1574.94	361.63	3641.25			
May	99.16	522.67	678.06	338.67	2.17	874.28	1938.83	356.00	3667.00			
Jun	99.19	406.73	757.35	442.95	1.00	676.86	1626.95	623.05	3574.91			
Jul	99.08	483.67	290.13	461.20	3.93	1089.47	2170.00	413.13	4330.27			
Aug	99.31	247.50	290.15	442.40	1.00	656.90	1558.70	727.30	2936.40			
CRF Slag Analyses 2015												
	Cu%	%Fe	SiO <sub>2</sub> %	CaO %	MgO %	Co %	S %	Al <sub>2</sub> O <sub>3</sub> %	Fe <sub>3</sub> O <sub>4</sub> %	Total %	Fe/SiO <sub>2</sub>	
Jan	1.30	24.39	39.96	7.82	5.41	0.54	0.19	8.34	2.22	84.98	0.56	
Feb	1.55	24.93	40.99	7.10	3.89	0.71	0.21	8.61	2.66	87.98	0.65	
Mar	1.35	25.08	39.39	7.21	3.30	0.87	0.21	8.88	2.51	86.27	0.59	
Apr	1.20	25.68	38.89	7.24	3.94	0.62	0.22	8.72	2.33	86.50	0.63	
May	1.41	23.69	40.82	7.37	3.86	0.58	0.24	9.30	2.70	87.27	0.66	
Jun	0.43	24.99	40.54	7.70	3.99	0.46	0.28	8.93	1.17	87.32	0.62	
Jul	1.39	25.03	38.91	7.58	3.20	0.92	0.25	9.15	2.81	86.48	0.65	
Aug	1.18	25.28	37.52	7.60	3.45	0.86	0.21	9.46	2.93	85.58	0.68	