



# DESIGN OF COPPER ELECTROWINNING CIRCUIT USING CONVENTIONAL CELLS

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Design of copper electrowinning circuit using conventional cells

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# 1. Introduction

Copper electrowinning is the recovery of copper metal onto the cathode from electrolyte. The electrolyte may be the leach solution or the purified solution from solvent extraction. The copper electrowinning cell-house using the conventional cells has many cells. Each cell is rectangular box having 1 m wide, from 1.5 to 2 m deep and from 5 to 7 m long. The copper electrowinning cell contains many cathodes and the same number +1 anodes. Copper is plated on to both sides of the cathode sheets, while water is oxidized to form oxygen gas and hydrogen ions on the anode. The rich electrolyte is fed into the cells and then is passed through the cells. Once the copper deposit on one side cathode has plated to the weight of ~60 kg, the cathodes are unloaded from the cell.

At the beginning of 1900, copper electrowinning using inert lead anodes was established as the method of purifying copper solution. In 1917, the first large plant started using leach solution from vat leach. The cathode was the starter sheet and the anode was the Pb-Sb alloy [1]. The introduction of copper solvent extraction as the interface between leaching and electrowinning plants improved the quality of copper deposition. Rolled and cast Pb-Ca-Sn anodes have taken place of Pb-Sn anodes because Pb-Ca-Sn anodes have presented better mechanical properties, corrosion resistance and long life time [1]. Dimensionally stable anodes (DSA) used in the alkali industry have been proposed and tested in copper electrowinning cell-house. DSA are commonly fabricated from titanium covered with platinum or ruthenium oxide. DSA are chemically stable and do not introduce impurities into the cell. DSA is very expensive due to the precious metals used in manufacturing [1].

The use of starter sheet begins with the copper electrowinning technology. The starter sheets demands more work for manufacturing and using in the cell-house. Currently permanent cathode blanks are used in place of starter sheets. Copper is electrodeposited on a mother plate of titanium or stainless steel. Stainless steel technology has been growing in popularity compared to titanium because of the significantly lower initial capital expenditure [1] [2].

Introduction of copper solvent extraction technology has forbidden the used of colloidal additives in the copper electrowinning because of the potential problems associated with the formation of crud in solvent extraction. The use of a high molecular weight guar gum derivative as a leveling agent for leach/solvent extraction/copper electrowinning has been recognized. It is been recognized also that small addition of cobalt to copper electrolyte decreases the corrosion of Pb anodes and the contamination of cathode in Pb [1] [3].

In copper electrowinning cell-house, concrete cells have been used for a long period. Concrete cells used Liners to protect the concrete structure. Lead was used as a lining material at the beginning. But Lead liners oxidized and frequently leaked. Lead was replaced with other liner materials as PVC, fiber-reinforce plastic and HDPE. Recently the trend has been towards the use of polymer concrete cells. The polymer concrete cell requires no liner or buffer sheets [1] [3].

However there are many questions which remain such as the value of the current density when the new copper electrowinning circuit is designed or why the numbers of cathodes per cells are different for the copper production rate of 20 and 40 ktpa. These questions relate much more to the determination of the number and dimensions of equipment.

The purpose of this publication is to gives the procedure of copper electrowinning circuit equipment sizing and copper electrolyte flowrate simulation. Therefore this publication starts with the second chapter which explains the fundamental principles of copper electrowinning, copper electrolysis and Faradays law.

The third chapter gives mathematical expressions which give the plant equipment sizing such as number of cell house cathodes, harvest cycle, number of cathodes per cell, number of cells per cell-house, rectifier and cathode stripping machine capacity based on the average number of overhead crane revolutions between cells and stripping per day.

The fourth chapter gives the characteristic of electrolyte flow and the mathematical expression which gives the liquid specific gravity as a function of liquid element composition, the cathode face velocity in the industrial practice, number of cells in the scavenger and commercial circuit, and the electrolyte distribution.

The fifth chapter explain the procedure of copper electrowinning circuit simulation by using Microsoft excel solver program step by step. The procedure of copper electrowinning circuit simulation concerns two cases. The first case is the simulation of a new copper electrowinning plant consisting to find number and size of equipment and flowrate of electrolytes for a known copper production rate. The second case is the simulation of an old copper electrowinning plant consisting to find the copper production, operating current density, and electrolyte flowrates from a known transferred copper rate in the copper electrowinning circuit.

## 2. Fundamental principles

Copper electrowinning is based on the copper electrolysis principle which uses the electrical power to reduce copper ions in solution to copper metal on the cathode and to oxidize water on the anode in oxygen gas and hydrogen ions [3]. The chemical equation (a) gives the copper electrolysis global chemical reaction.



Copper electrowinning circuit of a plant having L/SX/EW configuration and using permanent cathode technology consists of a stainless steel cathode, an inert anode (lead alloy), and the copper electrolyte that contains  $\text{Cu}^{+2}$ ,  $\text{Fe}^{+3}$ ,  $\text{Fe}^{+2}$ ,  $\text{Co}^{+2}$ , and  $\text{SO}_4^{2-}$  as major elements. The predominant reactions at the cathode are given by the chemical reactions (b) and (c) and the predominant reactions at the anode surface are given by the chemical reactions (d) and (e).



At the cathode, the mathematical expression (1) gives the current density which is the sum of current densities used respectively for the chemical reactions (b) and (c) [4].

$$i_c = i_{\text{Cu}} + i_{\text{Fe}}^l \quad (1)$$

Where " $i_c$ " is cathode current density ( $\text{A}/\text{m}^2$ ), " $i_{\text{Cu}}$ " is current density used to plate copper ( $\text{A}/\text{m}^2$ ), and " $i_{\text{Fe}}^l$ " is limiting current density used to reduce  $\text{Fe}^{+3}$  ( $\text{A}/\text{m}^2$ ).

The iron limiting current density is the maximum value of current density that uses to reduce  $\text{Fe}^{+3}$  to  $\text{Fe}^{+2}$  onto the cathode. The iron current density is limited by the diffusion of  $\text{Fe}^{+3}$  ions the cathode surface.

The mass of copper deposited on the cathode is given by Faradays law. Faraday law is given by the mathematical expression (2).

$$M_{\text{Cu}} = \frac{1}{96.485} \times \frac{63.55}{2} \times T \times I \times \eta \quad (2)$$

Where " $M_{Cu}$ " is the mass of copper (gram), "96.485" is Faraday constant (coulombs per mole), "63.55" is copper molar mass (grams per mole), "2" is moles of electron per mole of copper, "T" is the time when current has been applied (seconds), "I" is the current amperage (Amps) and " $\eta$ " is current efficiency.

The values of current amperage and current efficiency are given by the mathematical expressions (3) and (4). "A" is the cathode active area ( $m^2$ ).

$$I = i_c \times A \quad (3)$$

$$\eta = \frac{i_{Cu}}{i_c} \quad (4)$$

### 3. Plant equipment sizing

#### 3.1. Production rate

Copper production rate of an electrowinning circuit is given by the mathematical expression (5).

$$PR = K \times A \times n \times OCD \times \eta \times 10^{-6} \quad (5)$$

Where "PR" is copper production rate (t/h), "K" is a constant (1.18576 grams of copper deposited per amp-hour), "A" is cathode active area (m<sup>2</sup>), "n" is the number of cathodes into the cell-house, "OCD" is operating current density (A/m<sup>2</sup>), and "η" is current efficiency.

##### 3.1.1. Cathode active area

Modern copper electrowinning circuit use permanent cathode technology with stainless steel cathode. There are two permanent cathode technologies; ISA process in late 70's and Kidd process in late 80's. Both methods use side edge strip. The main difference between ISA and Kidd process is related to the bottom of cathodes. The ISA process uses wax on the bottom of the cathode to prevent copper deposition (the two sheets of copper deposit are not connected). The Kidd process leaves the bottom exposed (the two sheets of copper deposit are connected) [1] [2].

Features of each technology related to the size of cathode are as follows:

ISA process

- 3 to 3.25 mm thick 316L stainless steel cathode plate.
- 1290 mm height x 1042 mm width cathode dimension.
- 2.41 m<sup>2</sup> cathode active area.

Kidd process

- 3 to 3.125 mm thick 316L stainless steel cathode plate.
- 1060 mm height x 1000 mm width cathode dimension.
- 2.32 m<sup>2</sup> cathode active area.

The usage rate per year of stainless steel cathode is estimated at 20% of the number of cathode in the cell-house for both permanent cathode technologies.

##### 3.1.2. Design current density

The mathematical expression (6) gives the value of the copper limiting current density from which copper powder starts to be produced [4].

$$I_{Cu}^l = z \times F \times D \times \frac{C_{Cu}}{\delta} \quad (6)$$

Where “ $I_{Cu}^l$ ” is the limiting current density, “ $z$ ” is moles of electrons per mole of copper, “ $F$ ” is Faraday constant, “ $D$ ” is the diffusion coefficient, “ $C_{Cu}$ ” is the bulk electrolyte tenor of copper, and “ $\delta$ ” is the boundary thickness.

The values of the boundary thickness and the diffusion coefficient are depended on the electrolyte properties and electrolyte agitation. In the modern copper electrowinning circuit using the conventional cell technology, the value of the copper limiting current density is ranged from 800 – 1000 A/m<sup>2</sup>.

It has been found for a conventional copper electrowinning cell that increasing the ratio of operating current density on the limiting current density decrease the size of the crystals that make up copper deposit from well-formed large crystals to very fine crystals or powdery deposits [5]. The range of operating current density that produces a compact structure of copper deposit is ranged from 270 – 350 A/m<sup>2</sup> for a spent electrolyte copper tenor varied from 30 to 35 g/l. In consequence, the value of adopted design current density for most of copper electrowinning circuit is 300 A/m<sup>2</sup>.

In the same way, it has been observed also that the compact structure of copper deposit has been obtained when the ratio of operating current density on the copper tenor in the spent electrolyte is less than 10 [5]. This rule is widely used in the industrial practice. The spent electrolyte copper tenor must be greater than 30 g/l for a design current density of 300 A/m<sup>2</sup>. This new rule opens the possibility to increase the operating current density up to 400 A/m<sup>2</sup>.

The modern copper electrowinning uses cold rolled Pb-Ca-Sn anodes having a high corrosion resistance. The life time of these anodes is ranged from 5 and 10 years at the operating current density ranged from 280 -320 A/m<sup>2</sup> [1]. The usage rate per year is estimated at 25% of the number of anodes in the cell-house.

### 3.1.3. Current efficiency

In the industrial copper electrowinning circuit, the current efficiency is the fraction of the current that is used to plate copper. The other fraction is the sum of the current losses which are caused generally by electrical short-circuits and the reduction of Fe<sup>+3</sup> ions at the cathode. The mathematical expression (7) gives the value of current efficiency when the reduction of Fe<sup>+3</sup> ions is the only current loss [4]. The mathematical expression (7) shows that the current efficiency increases with increasing the operating current density, increasing the iron boundary thickness, and decreasing iron tenor in copper electrolyte.

$\eta = 1 - F \times D_{Fe} \times \frac{C_{Fe}}{\delta \times OCD}$	(7)
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Where “ $F$ ” is faraday constant, “ $D_{Fe}$ ” is the coefficient diffusion of Fe<sup>+3</sup> ions, “ $C_{Fe}$ ” is the electrolyte tenor of Fe<sup>+3</sup> ions, “ $\delta$ ” is the iron boundary thickness, and “ $OCD$ ” is the operating current density.

In the industrial practice, the copper electrowinning circuit using a conventional cell and operating with the operating current density ranged from 280 to 320 A/m<sup>2</sup>, the iron tenor in the copper electrolyte is maintained at maximum value of 2 g/l to have current efficiency ranged from 0.88 to 0.92 [1]. The iron tenor is maintained in the copper electrowinning circuit by bleeding the copper spent electrolyte. In consequence the flowrate value of iron bleed is ranged from 1 to 4% of copper spent electrolyte flowrate for the ratio of stripped copper on stripped iron from loaded organic ranged from 500 – 1000.

Manganese into the copper electrolyte is leaded to permanganate formation which degrades the SX organic in the stripping circuit. The ratio ferrous iron on manganese must be greater than 10 (Eh (Ag/AgCl) of copper electrolyte must be less than 600 mV). In consequence, the minimum total iron tenor into the copper electrolyte must be 1 g/l.

When the operating current density is increased to a value ranged from 370 to 400 A/m<sup>2</sup>, the value of the boundary thickness  $\delta$  decreases because of the electrolyte agitation causes by oxygen evolution. In this condition, the iron limiting current increases. In consequence, the iron tenor in the copper electrolyte must be  $\sim 1$  g/l to have a value of current efficiency ranged from 0.88 to 0.92.

### 3.2. Harvest cycle

The copper electrowinning circuits using the permanent cathode need stripping machines to separate the copper deposit from the stainless steel blank. The thickness of the copper deposit must be  $\sim 5$  mm for a good operation on stripping machine. The harvest cycle depends on the operating current density, the current efficiency and the one side cathode active area. There are 3 cases:

**First case:** the harvest cycle is calculated from the weight of the one side copper deposit. The mathematical expression (8) gives the value of the harvest cycle (days) from the weight of the one side of copper deposit. The weight of one side copper deposit is ranged from 40 to 60 kg

$$HC \text{ (days)} = \frac{M \times 1000}{K \times A \times OCD \times \eta \times 12} \quad (8)$$

Where "HC" is harvest cycle (days), "M" is the weight of one side copper deposit (kg), "K" is 1.18576, "A" is cathode active area, "OCD" is operating current density (A/m<sup>2</sup>), and " $\eta$ " is current density.

**Second case:** the harvest cycle is calculated from the thickness of the one side copper deposit: The mathematical expression (9) gives the value of the harvest cycle (days) from the thickness of the one side of copper deposit. The value of the thickness of the one side copper deposit is 5 mm.

$$HC \text{ (days)} = \frac{5 \times 8.92 \times 1000}{K \times OCD \times \eta \times 24} \quad (9)$$

Where "HC" is harvest cycle (days), "5" is the thickness of one side copper deposit (mm), "8.92" is the specific gravity of copper deposit (t/m<sup>3</sup>), "K" is 1.18576, "OCD" is operating current density (A/m<sup>2</sup>), and " $\eta$ " is current density.

The weight of one side copper deposit is given by the mathematical expression (10).

$$WOS \text{ (kg)} = K \times A \times OCD \times \eta \times 10^{-3} \times HC \times 12 \quad (10)$$

Where "WOC" is the weight of one side copper deposit, "HC" is harvest cycle (days), "K" is 1.18576, "OCD" is operating current density (A/m<sup>2</sup>), "A" is the cathode active area (m<sup>2</sup>), and " $\eta$ " is current density.

**Third case:** In the copper electrowinning circuit, the target is the strip all the cell-house cathodes in one week. In consequence the harvest cycle is fixed at 7 days. The mathematical expression (10) gives the weight of one side copper deposit.

### 3.3. Number of cathodes per cell and number of cells in the cell-house

The number of cathodes per cell times the number of cells into the cell-house equals the total number of cathodes into the cell-house (n). Currently, the number of cathodes per cell must be a multiple of 3 because the unloaded cathode method from the cell is: every third cathode is unloaded per crane over cell length. With this unloaded cathode method, the current density increases from OCD to  $\frac{4}{3} \times \text{OCD}$  A/m<sup>2</sup> on the cathodes that remain into the cell.

Table 1 gives production rate, number of cells into the cell-house, and number of cathodes per cell for existing copper electrowinning circuits using permanent cathode technology [6].

Table 1A: Production rate, number of cathodes per cell, and number of cells into the cell-house for existing plant

Production rate, ktpa	5.5	9.5	11.8	13	18	20	30
Number of cells per cell house	32	52	102	74	92	84	80
Number of cathodes per cell	33	30	21	33	33	45	69

Table 1B: Production rate, number of cathodes per cell, and number of cells into the cell house for existing plant

Production rate, ktpa	42	45	55	70	82.5	115	225
Number of cells per cell house	156	164	188	160	264	280	600
Number of cathodes per cell	57	57	60	69	60	66	66

The numbers of cells into the cell house are the multiple of 2 because the cell-house are designed to have two lines having equal number of cells for an optimum arrangement of bus-bar. Figure 1 give current distribution for a group of cells connected to one rectifier.

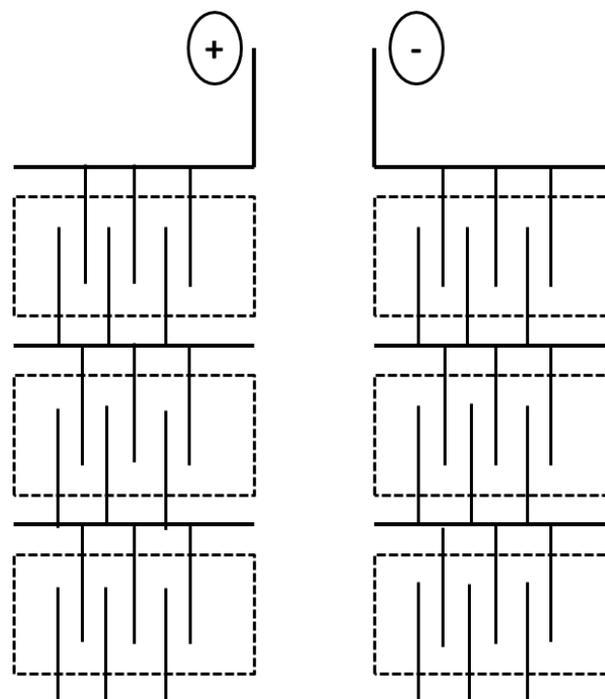


Figure 1: current distribution

Table 1 also shows that the number of cathodes per cell is ranged from 21 to 69. The number of cathodes per cell increase with increasing the copper production rate. The maximum value of the number of cathodes per cell of 69 is limited by the unload method of cathode from cell which pull out cathode over the length cell. For the plants located in the colder climate, the number of cathodes per cell can reach 80 to reduce a building space.

From the mathematical expression (5), it is possible to obtain the number of cathodes into the cell-house when the design current density, cathode active area and current efficiency are known. The question remains how to find the optimal arrangement of the number of cathodes per cell and the number of cells into the cell-house for a given number of cathodes into the cell-house. For this, the trick using the number of crane revolutions per crane and per day observed in the existing copper electrowinning will be used.

The crane revolution is the path of crane from the cell to the stripping machine and from the stripping machine to the cell. Table 2 gives the number of crane revolutions per crane and per day for the existing copper electrowinning circuits having operating current density ranged from 280 to 320 A/m<sup>2</sup>, the number of cathodes per cell ranged from 21 to 69, and using the permanent cathode technology [6].

Table 2: Number of crane revolutions per crane and per day for different production rates

Production rate, ktpa	9.5	11.8	13	18	20	30	70
Operating current density, A/m <sup>2</sup>	320	312	280	300	280	300	280
Number of cells per cell house	52	102	74	92	84	80	160
Number of cathodes per cell	30	21	33	33	45	69	69
Number of cathodes per cell house	1560	2142	2442	3036	3780	5520	11040
Harvest cycle, days	5	7	7	7	7	7	7
Number of cathodes harvested per day	312.0	306.0	348.9	433.7	540.0	788.6	1571.1
Number of cathodes unloaded per crane	10	7	11	11	15	23	23
Number of crane revolutions per day	31.20	43.71	31.71	39.43	36.00	34.29	68.57
Number of cranes	1	1	1	1	1	1	2
Number of crane revolutions per day per crane	31.20	43.71	31.71	39.43	36.00	34.29	34.29

Table 2 shows that the number of crane revolutions per day and per crane is varied from 31.20 to 43.71. For a new copper electrowinning circuit using the permanent cathode and having the design current density ranged from 280 to 320 A/m<sup>2</sup>, the number of cells into the cell-house and the number of cathodes per cell will be set up to have the number of crane revolutions per day and per crane ranged from 31 to 44. This value makes it possible not to have an interruption in the copper production.

Table 3 gives examples of the number of cells into the cell-house and the number of cathodes per cell for the copper electrowinning. The values having the red color are the data. The other values are calculated as follow:

The production rate (t/h) is given by the mathematical expression (11).

$$PR = \frac{\text{production rate (tpa)}}{8322} \quad (11)$$

Where "PR" is the production rate (t/h) and "8322" is the working hours per year of the cell-house.

Number of cell-house cathodes is calculated using the mathematical expression (12).

$$n = \frac{PR \times 10^6}{K \times A \times DCD \times \eta} \quad (12)$$

Where “n” is the number of cell-house cathodes, “PR” is production rate (t/h), “K” is a constant (K is 1.18576 is grams of copper deposited par amp-hour), “A” is cathode active area (m<sup>2</sup>), “DCD” is design current density (A/m<sup>2</sup>) and “η” is current efficiency.

The number of cathodes per cell is variable. The starting value of the number of cathodes per cell is 69. The number of cells into cell-house is given by the mathematical expression (13).

$$\text{Number of cells} = \frac{\text{Number of cell house cathodes}}{\text{Number of cathodes per cell}} \quad (13)$$

If the number of cells into the cell-house is not a multiple of 2, Design number of cell into the cell-house is the first number multiple of 2 which is below the number of cells.

Design number of cell-house cathodes is given by the mathematical expression (14).

$$\text{Design number of cell house cathodes} = \text{Number of cathodes per cell} \times \text{Design number of cells} \quad (14)$$

Number of unloaded cathodes per day is given by the mathematical expression (15).

$$\text{Number of unloaded cathodes per day} = \frac{\text{Design number of cell house cathodes}}{\text{Harvest cycle (days)}} \quad (15)$$

The number of unloaded cathodes per crane is given by the mathematical expression (16) (the crane is designed to lift per pull every 3rd cathode over cell length).

$$\text{Number of unloaded cathodes per crane} = \frac{\text{Number of cathodes per cell}}{3} \quad (16)$$

The total number of crane revolutions per day is given by the mathematical expression (17).

$$\text{Total number of crane turns per day} = \frac{\text{Number of unloaded cathodes per day}}{\text{Number of unloaded cathodes per crane}} \quad (17)$$

The number of cranes is variable. The number of crane will be changed from 1, 2, 3... If the number of crane revolutions per day and per crane is out of the range (30-44), the number of cathodes per cell is changed to low value 63, 60, 57.... The operation stops when the number of crane revolutions per day and per crane is between 31 and 44.

The number of crane revolutions per day and per crane is giving by the mathematical expression (18).

$$\text{Number of crane revolution per day and per crane} = \frac{\text{Total Number of cranne revolutions per day}}{\text{Number of cranes}} \quad (18)$$

The operating current density is given by the mathematical expression (19).

$$OCD = \frac{PR \times 10^6}{K \times A \times Dn \times \eta} \quad (19)$$

Where “OCD” is operating current density (A/m<sup>2</sup>), “Dn” is the design number of cell-house cathodes, “PR” is production rate (t/h), “K” is a constant (K is 1.18576 is grams of copper deposited par amp-hour), “A” is cathode active area (m<sup>2</sup>), and “η” is current efficiency.

Table 3A: Estimation of the number of cells into the cell-house and the number of cathodes per cell

	1	2	3	4	5	6	7
Production rate, ktpa	45	45	45	45	45	45	45
Working hours per year	8322	8322	8322	8322	8322	8322	8322
Production rate, t/h	5.41	5.41	5.41	5.41	5.41	5.41	5.41
Type of cathode blank	ISA						
Cathode active area, m <sup>2</sup>	2.41	2.41	2.41	2.41	2.41	2.41	2.41
Design current density, A/m <sup>2</sup>	300	300	300	300	300	300	300
Current efficiency	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Constant K	1.1858	1.1858	1.1858	1.1858	1.1858	1.1858	1.1858
Design harvest cycle, days	7	7	7	7	7	7	7
Number of cathodes per cell house	7008.2	7008.2	7008.2	7008.2	7008.2	7008.2	7008.2
Number of cathodes per cell	69	48	36	30	24	24	21
Number of cells per cell house	101.6	146.0	194.7	233.6	292.2	292.0	333.7
Design number of cells per cell house	100	146	194	232	292	292	332
Design number of cell house cathodes	6900	7008	6984	6960	7008	7008	6972
Number of unloaded cathodes per day	985.7	1001.1	997.7	994.3	1001.3	1001.1	996.0
Number of unloaded cathodes per crane	23	16	12	10	8	8	7
Total Number of crane revolutions per day	42.9	62.6	83.1	99.4	125.1	125.1	142.3
Number of cranes	1	2	2	3	3	4	4
Number of crane revolutions per day per crane	42.86	31.29	41.57	33.14	41.71	31.29	35.57
Operating current density, A/m <sup>2</sup>	301.70	300.01	301.04	302.08	300.01	300.01	301.56

Table 3B: Estimation of the number of cells per cell house and the number of cathodes per cell

	8	9	10	11	12	13	14
Production rate, ktpa	30	30	30	30	30	20	20
Working hours per year	8322	8322	8322	8322	8322	8322	8322
Production rate, t/h	3.60	3.60	3.6	3.6	3.60	2.4	2.4
Type of cathode blank	ISA						
Cathode active area, m <sup>2</sup>	2.41	2.41	2.41	2.41	2.41	2.41	2.41
Design current density, A/m <sup>2</sup>	300	300	300	300	300	300	300
Current efficiency	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Constant K	1.1858	1.1858	1.1858	1.1858	1.1858	1.1858	1.1858
Design harvest cycle, days	7	7	7	7	7	7	7
Number of cathodes per cell house	4672.1	4672.1	4672.1	4672.1	4672.1	3114.8	3114.8
Number of cathodes per cell	63	45	30	24	21	42	30
Number of cells per cell house	74.2	103.8	155.7	194.7	222.5	74.2	103.8
Design number of cells per cell house	74	102	154	194	222	74	102
Design number of cell house cathodes	4662	4590	4620	4656	4662	3108	3060
Number of unloaded cathodes per day	666.0	655.7	660	665.1	666	444.0	437.1
Number of unloaded cathodes per crane	21	15	10	8	7	14	10
Total Number of crane revolutions per day	31.7	43.7	66.0	83.1	95.1	31.7	43.7
Number of cranes	1	1	2	2	3	1	1
Number of crane revolutions per day per crane	31.71	43.71	33.0	41.57	31.71	31.71	43.7
Operating current density, A/m <sup>2</sup>	300.05	305.37	303.39	301.04	300.65	300.65	305.37

The results of Table 3 show that:

- For a production rate of 45 ktpa with one crane, there is only one arrangement of number of cells into the cell-house and number of cathodes per cell (column 1 of Table 3).
- For a production rate of 45 ktpa with two cranes, there are 5 possibilities of arrangements which give the number of crane revolutions per day and per crane ranged from 31 to 44. The number of cathodes per cell is ranged from 36 to 48 (columns 2 and 3 of Table 3).
- For a production rate of 45 ktpa with 3 cranes, there are 3 possibilities of arrangements which give the number of crane revolutions per day and per crane ranged from 31 to 44. The number of cathodes per cell is ranged from 24 to 30 (columns 4 and 5 of Table 3).
- For a production rate of 45 ktpa with 4 cranes, there are 2 possibilities of arrangements which give the number of crane revolutions per day and per crane ranged from 31 to 44. The number of cathodes per cell is ranged from 21 to 24 (columns 6 and 7 of Table 3).
- For a production rate of 30 ktpa with one crane, there are 7 possibilities of arrangements which give the number of crane revolution per day and per crane ranged from 31 to 44. The number of cathodes per cell is ranged from 45 to 63 (columns 8 and 9 of Table 3).
- For a production rate of 30 ktpa with two cranes, there are 3 possibilities of arrangements which give the number of crane revolutions per day per crane ranged from 31 to 44. The number of cathodes per cell is ranged from 24 to 30 (columns 10 and 11 of table 3).
- For a production rate of 30 ktpa with 3 cranes, there is one possibility of arrangements which give the number of crane revolutions per day per crane ranged from 31 to 44. The number of cathodes per cell is 21 (columns 12 of table 3).
- For a production rate of 20 ktpa with one crane, there are 4 possibilities of arrangements which give the number of crane revolutions per day per crane ranged from 31 to 44. The number of cathodes per cell is ranged from 30 to 42 (columns 13 and 14 of table 3).

The optimum configuration which present low capital cost of the cell-house is the one which have the high value of the number of cathodes per cell.

### 3.4. Rectifier size and number

#### 3.4.1. Rectifier size

The size specification of rectifier is based on the maximum DC current amperage and DC voltage. The mathematical expression (20) gives the value of the operating current amperage. The value of operating current amperage must range from 70 to 80% of the maximum DC current amperage of the rectifier. The bus-bar must be sized on the maximum DC current amperage of the rectifier.

$$I_{OA} = OCD \times A \times CC \times 10^{-3} \quad (20)$$

Where " $I_{OA}$ " is the operating current amperage (KA),  $OCD$  is the operating current density ( $A/m^2$ ),  $A$  is the cathode active area ( $m^2$ ), and  $CC$  is the number of cathodes per cell.

The maximum DC current amperage of the rectifier is given by the mathematical expression (21).

$$I_{MA} = \frac{I_{OA}}{0.75} \quad (21)$$

Where " $I_{MA}$ " is the maximum DC current amperage (KA) and " $I_{OA}$ " is the operating current amperage (KA).

The maximum current density of the rectifier is given by the mathematical expression (22).

$$MCD = \frac{I_{MA} \times 1000}{A \times CC} \quad (22)$$

Where "MCD" is the maximum current density of the rectifier, " $I_{MT}$ " is the maximum DC current amperage of the rectifier (KA), "A" is the cathode active area ( $m^2$ ), and "CC" is the number of cathodes per cell.

The mathematical expression (23) gives the value of total voltage.

$$V_T = V_{TC} + V_L \quad (23)$$

Where " $V_T$ " is the total voltage (V), " $V_{TC}$ " is the total cell voltage (V), and " $V_L$ " is bus-bar and losses voltage (V).

The mathematical expression (24) gives the value of total cell voltage.

$$V_{TC} = V_C \times CR \quad (24)$$

Where " $V_C$ " is the cell voltage (V) and "CR" is the number of cells in series connected to the rectifier.

The mathematical expression (25) gives the value of cell voltage.

$$V_C = V_e + \rho_c + \rho_a + V_R \quad (25)$$

Where " $V_e$ " is the equilibrium cell voltage, " $\rho_c$ " is the cathode over-potential, " $\rho_a$ " is the anode over-potential, and " $V_R$ " is the resistance drop voltage

Equilibrium cell voltage ( $V_e$ ) is given by the mathematical expression (26).

$$V_e = E_a - E_c \quad (26)$$

Where " $E_a$ " is the electrode standard potential of the chemical reaction (d) (1.23 V) and " $E_c$ " is the electrode standard potential of the chemical reaction (b) (0.34V).

The value of cathode over-potential operating at the operating current density of 300 A/ $m^2$  is ~0.08 V. the value of anode over-potential operating with the anode (Pb6%Sb) at the operating current density of 300 A/ $m^2$  is ~0.6 V.

The resistance drop voltage is the sum of:

- Electrode contact resistance voltage drop.
- Electrode internal resistance drop.
- Electrolyte resistance voltage drop.

**Electrode contact voltage drop:**

In the modern copper electrowinning cell-house, the electrode contact voltage drop is ranged from 5 to 25% of the total cell voltage.

**Electrode internal and electrolyte resistance voltage drops:**

The mathematical expression (27) gives the electrode internal and electrolyte resistance voltage drops.

$$V_R = OCD \times \Omega \times L \quad (27)$$

Where " $V_R$ " is the resistance voltage drop (V), "OCD" is the operating current density ( $A/m^2$ ), " $\Omega$ " is the material resistivity ( $\Omega\text{-m}$ ), and "L" is the length of the material (m).

- Electrode internal resistance voltage drop

The electrical resistivities of stainless steel and lead are respectively  $6.9 \times 10^{-7}$  and  $2.2 \times 10^{-7}$   $\Omega\text{-m}$ . In consequence the electrode internal resistance drop is negligible.

- Electrolyte resistance voltage drop

In the modern cell-house, the value of the cathode-cathode center-line distance is 95 mm, the cathode thickness is ~3 mm, and the anode thickness is ~6 mm. In consequence the distance between cathode and anode is ~43 mm. the value of the resistivity of the electrolyte containing 35 g/l of copper and 180 g/l of acid at the temperature of 45°C is ~0.0179  $\Omega\text{-m}$ .

The mathematical expression (28) gives the value of the cell voltage with a value of operating current density ranged from 280 to 400  $A/m^2$ .

$$V_C = \frac{1.57 + 7.69 \times 10^{-4} \times OCD}{1-a} \quad (28)$$

Where " $V_C$ " is the cell voltage (V), "OCD" is the operating current density ( $A/m^2$ ), "a" is the fraction of electrode contact resistance voltage into the cell voltage (average value 0.15).

The value of bus-bar and losses voltages is designed at 15% of total cell voltage. The mathematical expression (29) gives the value of bus-bar voltage and losses voltage.

$$V_L = V_{TC} \times \frac{15}{100} \quad (29)$$

The operating power of the rectifier (kW) is given by the mathematical expression (30).

$$OP = V_T \times I_{OA} \quad (30)$$

### 3.4.2. Rectifier number into the cell-house

The rectifiers used in the electrolysis of non-ferrous metal have the maximum DC amperage ranged from 5 to 100 kA and the DC voltage ranged from 100 to 1000 V. the number of cells connected to one rectifier is a multiple of 2 (Figure 1). The group of cells connected side by side is called block (Figure 1).

The number of cells connected to one rectifier is given by the mathematical expression (31).

$$\text{Number of cells per rectifier} = \frac{\text{Number of cells per cell house}}{\text{number of rectifier}} \quad (31)$$

The number of cells per bock is integer number and is given by the mathematical expression (32).

$$\text{Number of cells per block} = \frac{\text{Number of cells per rectifier}}{2} \quad (32)$$

The number of block into cell-house is given by the mathematical expression (33)

$$\text{Number of block per cell house} = \frac{\text{Number of cells per cell house}}{\text{Number of cells per block}} \quad (33)$$

Table 4 gives the number of rectifiers of copper electrowinning cell-house for two existing plants, Tenke Fungurume Mining (Democratic Republic of Congo) and Kansanshi (Zambia).

In Table 4, the number of rectifiers is changed from 1 to 3 for each cell-house. The design number of cells into the cell-house is greater than the number of cells into the cell-house for Tenke Fungurume Mining cell-house with 3 rectifiers and for Kansanshi cell-house with 2 and 3 rectifiers because the number of cells per block must be an integer number. The operating current amperage is 70% and 75% of the maximum DC current amperage of the rectifier respectively for Tenke Fungurume Mining and Kansanshi cell-houses.

The number of rectifiers in both the existing cell-houses of Tenke Fungurume Mining and Kansanshi is 2.

Table 4: Number of rectifiers for Tenke Fungurume Mining and Kansanshi

	Tenke Fungurume Mining			Kansanshi		
Production rate, ktpa	115	115	115	70	70	70
Working hours per year	8322	8322	8322	8322	8322	8322
Production rate, t/h	8322	8322	8322	8322	8322	8322
Type of cathode blank	ISA	ISA	ISA	ISA	ISA	ISA
Cathode active area, m <sup>2</sup>	2.41	2.41	2.41	2.41	2.41	2.41
Design current density, A/m <sup>2</sup>	300	300	300	300	300	300
Current efficiency	0.9	0.9	0.9	0.9	0.9	0.9
Constant K	1.1858	1.1858	1.1858	1.1858	1.1858	1.1858
Design harvest cycle, days	7	7	7	7	7	7
Number of cathodes per cell house	18527.5	18527.5	18527.5	10901.7	10901.7	10901.7
Number of cathodes per cell	66	66	66	69	69	69
Number of cells per cell house	280.7	280.7	280.7	158.0	158.0	158.0
Design number of cells per cell house	280	280	282	158	160	162
Design number of cell house cathodes	18480	18480	18612	10902	11040	11178
Number of unloaded cathodes per day	2640.0	2640.0	2658.9	1557.4	1577.1	1596.9
Number of unloaded cathodes per crane	22	22	22	23	23	23
Total Number of crane revolutions per day	120.0	120.0	120.9	67.7	68.6	69.4
Number of cranes	3	3	3	2	2	2
Number of crane revolutions per day per crane	40.00	40.00	40.29	33.86	34.29	34.71
Operating current density, A/m <sup>2</sup>	290.7	290.7	288.7	300.0	296.2	292.6
Number of rectifiers per cell house	1	2	3	1	2	3
Number of cells per rectifier	280	140	94	158	80	54
Number of cells per block	140	70	47	79	40	27
Number of block per cell house	2	4	6	2	4	6
Operating current amperage, kA	46.25	46.25	45.92	49.89	49.86	48.65
Maximum current amperage, kA	66.07	66.07	65.60	66.51	65.68	64.87
Maximum current density, A/m <sup>2</sup>	415.35	415.35	412.40	399.99	394.99	390.11
Total voltage, V	708.4	354.20	237.02	399.74	202.40	136.62

### 3.5. Cathode stripping machine size

There are two types of stripping machine, ISA process and Kidd process. There two stripping methods, manual and machine.

The mathematical expression (34) gives the size of the capacity of stripping machine.

$$M_c = \frac{n}{HC \times WHS} \quad (34)$$

Where " $M_c$ " is the capacity of stripping machine (cathodes/hour), " $n$ " is the design number of cathodes per the cell-house, " $HC$ " is harvest cycle (days), and " $WHS$ " is working hours of stripping machine per day.

The working hours of the stripping machine using manual method is 19 hours per day.

## 4. Material flowrates

### 4.1. Material parameters

#### 4.1.1. Solid parameter

Solid into the cell-house is the copper deposit. The copper deposit is characterized by a mass ( $M_s$ ) expressed in (ton).

#### 4.1.2. Gas parameter

Gas into the cell-house is the oxygen gas. The oxygen gas is characterized by a mass ( $M_G$ ) expressed in (ton).

#### 4.1.3. Liquid parameters

Liquids into the cell-house are the copper electrolytes. The copper electrolytes are characterized by a mass ( $M_L$ ) expressed in (ton) and a volume ( $V_L$ ) expressed in ( $m^3$ ). The specific gravity ( $SG_L$ ) expressed in ( $t/m^3$ ) is the ratio of the mass on the volume of copper electrolyte. The mathematical expression (35) gives the relationship that links the mass, the volume and the specific gravity of copper electrolyte.

$$SG_L = \frac{M_L}{V_L} \quad (35)$$

There are two methods for obtaining the specific gravity of liquid, the laboratory method and the chemical composition method.

#### 4.1.4. Laboratory method

When it is possible to have physically the liquid, the laboratory method for obtaining the specific gravity of liquid is as follows:

- Put the liquid in a test tube of one liter to the mark of a liter,
- Weigh the volume of one liter of liquid (g),
- And the ratio of weight on the one liter volume of liquid gives the specific gravity.

The specific gravity obtained in this condition is the approximated value at ambient temperature.

#### 4.1.5. Chemical composition method

A liquid is homogeneous mixture of solvent and solutes. In this publication, the solvent is water and solutes are the elements appearing into the copper electrolyte and dissolved in water as sulfate. These elements appearing in the copper electrolyte are listed in the Table 5.

The index “k” is an identification number of the chemical element in this publication. At this level, it is defined two other parameters; the mass of element of index “k” ( $M_k$ ) expressed in (kg) into the liquid and the tenor of element of index “k” ( $C_k$ ) expressed in ( $kg/m^3$ ) into the liquid. The mathematical expression (36) gives relationship that links the mass of element of index “k”, the tenor of element of index “k” and the volume of liquid.

Table 5: Elements appearing in copper electrolyte

Element	Index (k)
H <sub>2</sub> SO <sub>4</sub>	1
Cu	2
Co	3
Fe	4
Mn	5

$$M_k = V_L \times C_k \quad (36)$$

It has been observed for a liquid containing copper sulfate and sulfuric acid that [7]:

- The specific gravity of copper sulphate or sulphuric acid liquid is approximately a linear function of concentration expressed in (%).
- The specific gravity of liquids of equal concentration expressed in (%) of copper sulphate and of sulphuric acid is nearly identical.
- The specific gravity of liquid containing appreciable amounts of copper sulphate and sulphuric acid is dependent principally upon the total concentration (%) and is almost independent of their proportion.

These observations have been extended to the elements appearing in the copper electrolyte and the simplest method that allows having the approximated value of specific gravity of liquid from the chemical composition is given. The method consists of finding a total salt tenor ( $C_t^S$ ) expressed in (kg/m<sup>3</sup>) of elements as salt into the liquid. In this case, the salt is in form of sulfate. After, the total salt tenor must be applied in the mathematical expression (37) that gives the relationship between the liquid specific gravity and the total salt tenor of elements. The equation (37) comes from data that give the specific gravity of liquid as a function of tenor of element as salt in binary system [8].

$$SG_L = -6.139 \times 10^{-4} \times [C_t^S]^2 + 0.9742 \times C_t^S + 1000 \text{ (kg/m}^3\text{)} \quad (37)$$

Therefore, it is defined a constant  $\alpha_k$  of element of index “k”. The constant  $\alpha_k$  is the value to multiply to the tenor of element of index “k” to have the tenor as sulfate salt “ $C_k^S$ ”. The values of constant  $\alpha_k$  are given in Table 6. The value of tenor “ $C_k^S$ ” of element of index “k” is given by equation (38).

$$C_k^S = \alpha_k \times C_k \quad (38)$$

Table 6: value of constant  $\alpha_k$

Elément	Index (k)	$\alpha_k$
H <sub>2</sub> SO <sub>4</sub>	1	1.000
Cu	2	2.511
Co	3	2.629
Fe	4	2.719
Mn	5	2.747

Thus, the value of total salt tenor “ $C_t^S$ ” of elements in the liquid will be calculated according to equation (39).

$$C_t^s = \sum_1^k C_k^s = \sum_1^k \alpha_k \times C_k \quad (39)$$

Table 7 gives an example for obtaining the specific gravity from the chemical composition of given copper electrolyte. The result of Table 7 shows that the value of total salt tenor “ $C_t^s$ ” of elements in the copper electrolyte is 274.95 kg/m<sup>3</sup>. This value is the sum of tenors as sulfate salt of elements. By applying the value of total salt tenor of elements in the equation (37), the value of specific gravity of copper electrolyte “ $SG_L$ ” is 1221.44 kg/m<sup>3</sup>.

Table 7: Specific gravity from chemical composition of copper electrolyte

Element	Index (k)	Concentration	$\alpha_k$	$C_k^s$
		kg/m <sup>3</sup>		kg/m <sup>3</sup>
H <sub>2</sub> SO <sub>4</sub>	1	180	1.000	180.00
Cu	2	35	2.511	87.89
Co	3	0.1	2.629	0.26
Fe	4	2.5	2.719	6.80
$C_t^s$				274.95

## 4.2. Number of cells into the scavenger and commercial circuits

Figure 2 gives the configuration of copper electrolyte flows into a copper electro-winning circuit. The cell-house for the plant using L/SX/EW technology is split into two circuits, scavenger and commercial. The scavenger circuit receives the total flow of the advance electrolyte. The main purpose of the scavenger cells is to limit organic contamination of the cathode.

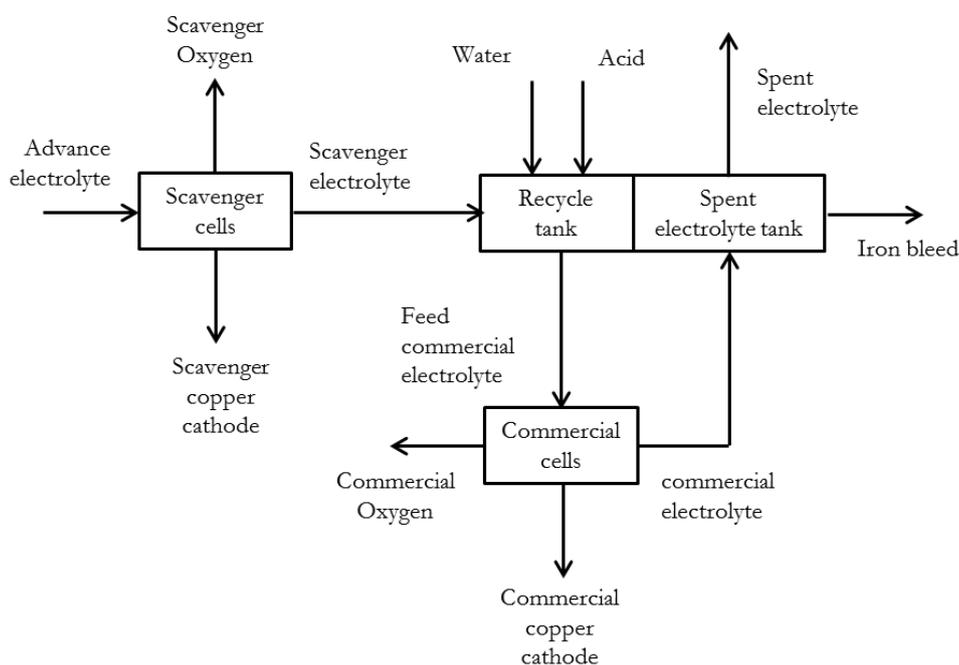


Figure 2: Electrolyte flow configuration into the cell-house

The repartition of cells between scavenger and commercial circuits depends on the known values of the electrolyte flowrate per cell into scavenger and commercial cells, copper tenor drop between advance and spent electrolytes, and number of cells into the cell-house. In the industrial practice, the proportion of cells into the scavenger circuit varies from 15 to 25% of the total number of cells into the cell-house.

There are two methods for obtaining the number of cells into the scavenger and commercial cells. These two methods are based on: the known value of cathode face velocity into the scavenger and commercial cells, and the known value of copper tenor drop per cell into the scavenger and commercial cells.

### Cathode face velocity

The electrolyte flowrate per cell depends on the cathode active area, the number of cathodes per cell, and the cathode face velocity. The cathode face velocity ((m<sup>3</sup>/h)/m<sup>2</sup>) is the ratio of the cell electrolyte flowrate on the cell cathode active area. The mathematical expression (40) gives the electrolyte flowrate per cell.

$$\text{Electrolyte flowrate per cell (m}^3\text{/h)} = A \times CC \times \text{cathode face velocity} \quad (40)$$

Where “A” cathode active area (m<sup>2</sup>), and “CC” is the number of cathodes per cell.

In the industrial practice, the value of the cathode face velocity is ranged from 0.08 to 0.14 (m<sup>3</sup>/h)/m<sup>2</sup>. Above the value of 0.14 (m<sup>3</sup>/h)/m<sup>2</sup>, the PbO<sub>2</sub> particles will remain in suspension. In the modern cell-house, the good value of the cathode face velocity is 0.12 (m<sup>3</sup>/h)/m<sup>2</sup>.

### Copper tenor drop per cell

The value of copper tenor drop per cell is ranged from 2 to 5 g/l. the electrolyte flowrate per cell is given by the mathematical expression (41).

$$\text{Electrolyte flowrate per cell (m}^3\text{/h)} = \frac{\text{PR} \times 1000}{\Delta\text{Cu} \times \text{number of cells per cell-house}} \quad (41)$$

Where “PR” is copper production rate (t/h), and “ΔCu” is the copper tenor drop per cell.

## 4.3. Cell-house Electrolyte distribution

Figure 3 gives the electrolyte distribution and the tanks for a copper electrowinning circuit.

The advance from the Cu SX is pumped to the cell-house via the electrolyte dual medium filter, which removes solid particles as well as the dissolved and entrained organics in the garnet and anthracite layers of the filter. The upper media is anthracite for organic removal and lower media is garnet for solid removal. The filtration efficiency must be greater than 90% for organic and solid removal. The filter specific flowrate is 12 (m<sup>3</sup>/h)/m<sup>2</sup> and the minimum number of filter units is 3. The holding tank volume live is setup to contain 3 consecutive electrolyte filter backwash cycles.

The filtered advance electrolyte is then warmed by exchanging the heat from the spent electrolyte. There is the heat exchanger temperature regulator after the first heat exchange working with raw water. The purpose of the second heat exchanger is to maintain the advance electrolyte temperature at 40°C.

Filtered advance electrolyte reports to the scavenger electrowinning cells. Outflow from the scavenger cells flows by gravity to the scavenger electrolyte sump from where it is pumped to the recycle tank. Feed commercial electrolyte is pumped to the commercial electrowinning cells. Outlet commercial electrolyte flows by gravity to the spent electrolyte tank. Spent electrolyte is pumped to the strip mixer-settlers via the electrolyte heat interchanger after removing

the iron bleed. The recycle tank and spent electrolyte tank are interconnected allowing the balance of the outlet commercial electrolyte to flow to the recycle tank.

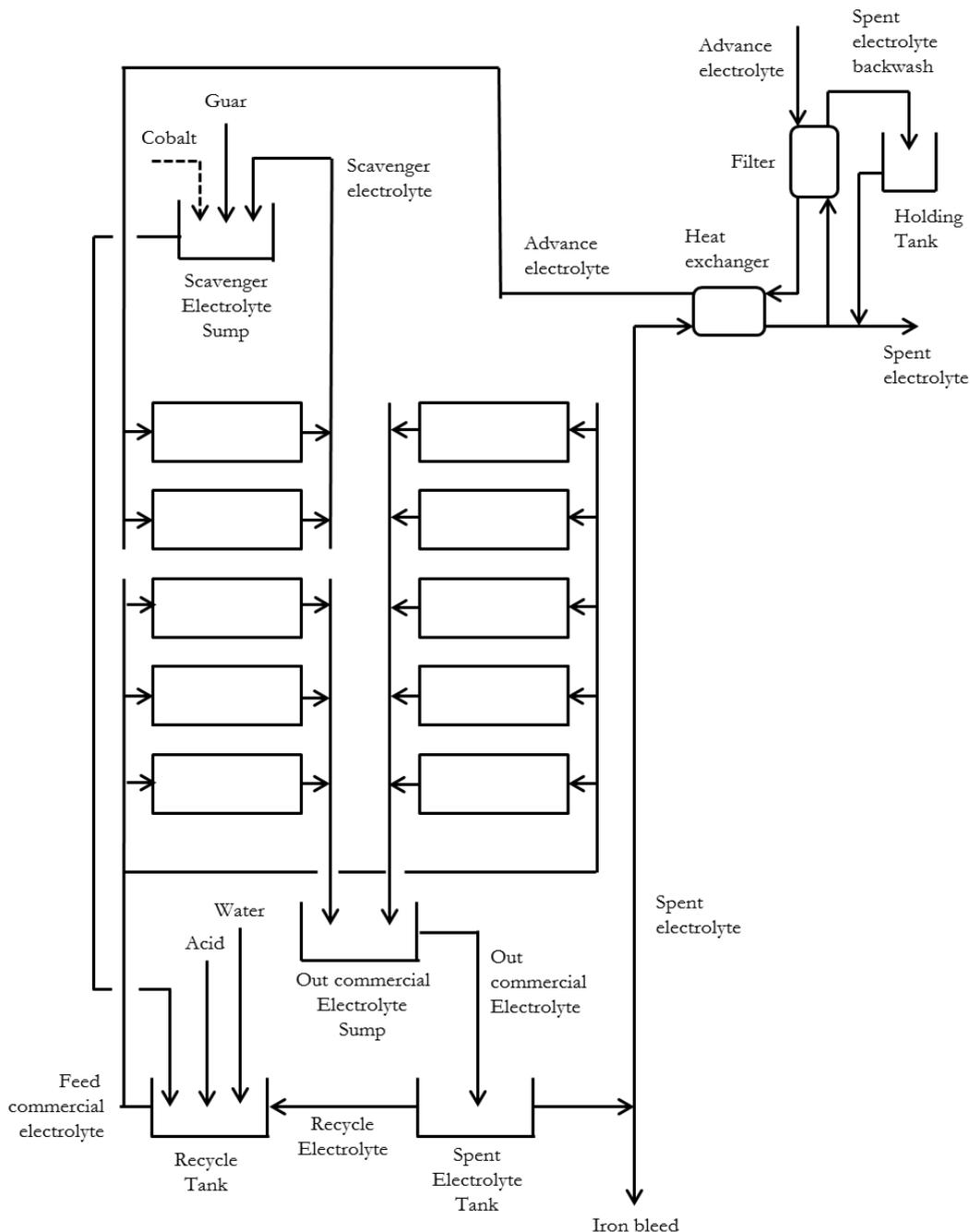


Figure 3: Electrolyte distribution and tanks of cell house

Water and acid make up are added to the recycle tank. Cobalt sulfate and Guar make up are added to the scavenger electrolyte sump. Cobalt composition into the copper electrolyte is 100 mg/l. Guar is smoothing agents commonly used in copper electrowinning circuit. The consumption rate of Guar is 200 g per ton of copper cathode produced. Guar is mixed with water at 0.75 % (w/w).

For copper electrowinning circuit coupled with solvent extraction, poly propylene balls are used for the acid mist on top of cells.

## 5. Procedure of copper electrowinning circuit simulation

### 5.1. General

The simulation of a copper electrowinning circuit will be done on an Excel spreadsheet (Microsoft). Excel spreadsheet gives numbers and formulas in the form of a table (rows and columns). The Excel spreadsheet is made of lines (numbered with numbers) and of columns (numbered with letters). The intersection of a row and a column is called "cell." A cell is identified by a letter and a number. The Excel spreadsheet can contain up to 65,536 rows and 256 columns, more than 17 million cells. Each of the cells of the spreadsheet can contain data (numbers, text, date...) which are entered directly or automatically calculated.

Microsoft excel solver program will be used for optimization of material flowrates of copper electrowinning circuit simulation. Excel Solver is the Microsoft add-in program used for what-if analysis. Excel solver program allows finding the optimum value for a formula in one cell.

### 5.2. Copper electrowinning circuit description

Figure 4 gives the flow diagram of copper electrowinning circuit. In this case, the copper electrowinning circuit is part copper production having L/SX/EW configuration. Each flow is designated by the number and the flow name.

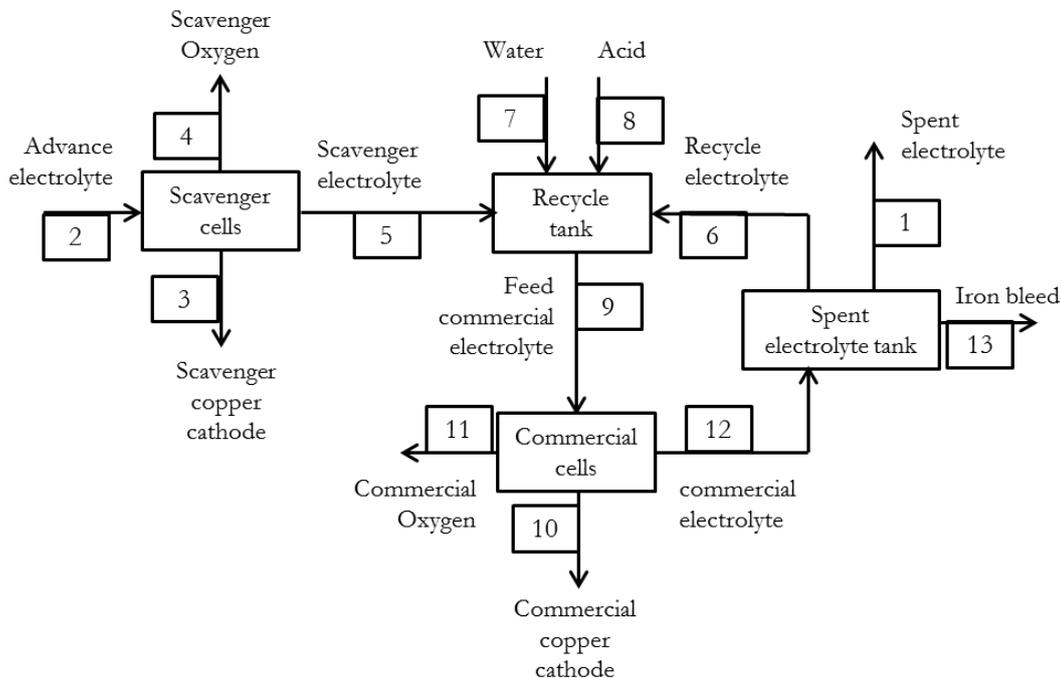


Figure 4: Copper electrowinning circuit with flow designations

### 5.3. Simulation of copper electrowinning circuit

#### 5.3.1. New copper electrowinning circuit

##### 5.3.1.1. Design data

The simulation procedure of a new copper electrowinning circuit will be explained through an example. Table 8 gives design data of an example of copper electrowinning circuit. Design data are used to simulate copper electrowinning circuit and sized the major equipment.

Table 8: Design data of copper electrowinning circuit

Designation		Unit
Production rate	70,000	t/y
Working hours per year	8322	hrs
Type of cathode blank	ISA	
Active area of Kidd cathode	2.41	m <sup>2</sup>
Design current density	300	A/m <sup>2</sup>
Current efficiency	0.90	
Constant K	1.1858	g/Amp-hour
Cathode face velocity	0.12	m/h
Constant $\alpha_1$ (acid)	1.000	
Constant $\alpha_2$ (copper)	2.511	
Constant $\alpha_4$ (iron)	2.719	
Spent electrolyte copper tenor	35	g/l
Spent electrolyte acid tenor	180	g/l
Advance electrolyte copper tenor	50	g/l
Spent electrolyte iron tenor	2	g/l
Ratio of stripped copper on stripped iron from SX	600	
Harvest cycle	7	days
Stripping machine working hours per day	19	hours

The simulation table of copper electrowinning circuit is given by Table 9 as it appears on the Excel spreadsheet. Table 9 is accompanied by 4 small tables:

- Simulation additional solver variable table: Simulation additional solver variable gives the value of solver variables which are not in Table 9.
- Simulation solver constraint table: Simulation solver constraint table gives solver constraints which will be used in the solver program.
- Simulation data table: Simulation data table gives data of copper electrowinning circuit which are in Table 8 (the color of the number is red).
- Simulation result table: Simulation result table gives the values of electrolyte flow parameter, and the number and size of major equipment.

In Table 9, each column gives the copper electrolyte flow as it appears on Figure 4. Each line gives flow parameters. Abbreviations mean:

- SpEl : Spent electrolyte
- AdEl : Advance electrolyte
- ScCC : Scavenger copper cathode
- ScOx : Scavenger oxygen
- ScEl : Scavenger electrolyte
- ReEl : Recycle electrolyte
- FCoEl: Feed commercial electrolyte
- CoCC: Commercial copper cathode
- CoOx: Commercial oxygen
- CoEl : Commercial electrolyte
- FeBl : Iron bleed

### 5.3.1.2. Simulation procedure of a new copper electrowinning circuit

The simulation procedure of a new copper electrowinning circuit is as follow:

#### 1. Calculation of number of cathodes per cell, design number of cells per cell house, number of cranes and number of rectifiers

- In the excel cell “F73” (design production rate – t/y), type “=F53/F54”.
- In the excel cell “F74” (number of cell house cathodes), type “=F73/ (F59\*F56\*F57\*F58\*10^-6)”(mathematical expression 6).
- In the excel cell “F75” (number of cathodes per cell), type the number “69” (maximum value).
- In the excel cell “F76” (number of cells per cell house), type “=F74/F75”.
- In the excel cell “F77” (design number of cells per cell house), type the number “158”
- In the excel cell “F78” (design number of cell house cathodes), type “=F75\*F77”.
- In the excel cell “F79” (number of unloaded cathodes per day), type “=F78/F69”.
- In the excel cell “F80” (number of unloaded cathodes per crane), type “=F75/3”.
- In the excel cell “F81” (number of crane revolutions per day), type “=F79/F80”.

The number into the excel cell “F81” is “67.71”. The number of crane must be “2” to have the number the number of crane revolutions per day and per crane between “31 - 44”.

- In the excel cell “F82” (number of cranes), type the number “2”.
- In the excel cell “F83” (number of crane revolutions per day and per crane), type “=F81/F82”.

The number into the excel cell “F83” is “33.86”. At this level, we decide to have 4 bocks (2 bocks per crane).

- In the excel cell “F84” (number of rectifiers), type number “2”.
- In the excel cell “F85” (number of cells per rectifier), type “=F77/F84”.
- In the excel cell “F86” (number of cells per block), type “=F85/2”.
- In the excel cell “F87” (number of blocks per cell house), type “=F77/F86”.

The number into the excel cell “F86” is “39.5”. The number of cells per block is not an integer number. At this level there are two options:

- To have one rectifier for the cell-house.
- To change the design number of cells into the cell-house as such as the number of cells per bock becomes an integer number with two rectifiers.

	A	B	C	D	E	F	G	H	I	J	K	
1												
2		<b>Table</b>	<b>9A</b>	<b>Simulation table of copper electrowinning circuit</b>								
3												
4				1	2	3	4	5	6	7		
5		Designation		Sp El	Ad El	Sc CC	ScOx	ScEl	Re El	Water		
6		Solid mass	t/h									
7		Gas Mass	t/h									
8		Liquid										
9		Mass	t/h									
10		Volume	m <sup>3</sup> /h									
11		SG	t/m <sup>3</sup>									
12												
13		$C_t^s$	g/l									
14		Cu	g/l									
15		Fe	g/l									
16		Acid	g/l									
17												
18		Cu	Kg/h									
19		Fe	Kg/h									
20		Acid	Kg/h									
21												
22		<b>Table</b>	<b>9B</b>	<b>Simulation table of copper electrowinning circuit</b>								
23												
24				8	9	10	11	12	13			
25		Designation		Acid	FCoEl	CoCC	CoOx	CoEl	FeBl			
26		Solid Mass	t/h									
27		Gas Mass	t/h									
28		Liquid										
29		Mass	t/h									
30		Volume	m <sup>3</sup> /h									
31		SG	t/m <sup>3</sup>									
32												
33		$C_t^s$	g/l									
34		Cu	g/l									
35		Fe	g/l									
36		Acid	g/l									
37												
38		Cu	Kg/h									
39		Fe	Kg/h									
40		Acid	Kg/h									
41												
42		<b>Simulation additional solver variable table</b>										
43		Fe bleed flowrate/spent electrolyte flowrate						%				
44												
45		<b>Simulation solver constraint table</b>										
46		Set objective			Constraint 5							
47		Constraint 1										
48		Constraint 2										
49		Constraint 3										
50		Constraint 4										
51												

	A	B	C	D	E	F	G	H	I	J	K
52	<b>Simulation table data</b>										
53		Production rate				<b>70,000</b>	t/y				
54		Working hours per year				<b>8,322</b>	hrs				
55		Type of cathode blank				<b>Kidd</b>					
56		Cathode active area				<b>2.32</b>	m <sup>2</sup>				
57		Design current density				<b>300</b>	A/m <sup>2</sup>				
58		Current efficiency				<b>0.9</b>					
59		Constant k				<b>1.1858</b>	g/ A-Hr				
60		Cathode face velocity				<b>0.12</b>	(m <sup>3</sup> /h/m <sup>2</sup> )				
61		Constant $\alpha_1$ (acid)				<b>1.000</b>					
62		Constant $\alpha_2$ (copper)				<b>2.511</b>					
63		Constant $\alpha_4$ (iron)				<b>2.719</b>					
64		Spent electrolyte copper tenor				<b>35</b>	g/l				
65		Spent electrolyte acid tenor				<b>180</b>	g/l				
66		Advance electrolyte copper tenor				<b>50</b>	g/l				
67		Spent electrolyte iron tenor				<b>2</b>	g/l				
68		Ratio of stripped Cu on Stripped Fe from SX				<b>600</b>					
69		Harvest cycle				<b>7</b>	days				
70		Stripping machine working hours per day				<b>19</b>	hrs				
71											
72	<b>Simulation table results</b>										
73		Design production rate					t/h				
74		Number of cell-house cathodes									
75		Number of cathodes per cell									
76		Number of cells per cell-house									
77		Design number of cells per cell-house									
78		Design number of cell-house cathodes									
79		Number of unloaded cathodes per day									
80		Number of unloaded cathodes per crane									
81		Number of crane revolutions per day									
82		Number of cranes									
83		Number of crane revolutions/day per crane									
84		Number of rectifier									
85		Number of cells per rectifier									
86		Number of cells per block									
87		Number of blocks per cell-house									
88		Operating current density					A/m <sup>2</sup>				
89		Electrolyte flowrate per cell					m <sup>3</sup> /h				
90		Number of cells/scavenger									
91		Design number of cells/scavenger									
92		Number of cells/commercial									
93		Operating current Amperage					kA				
94		Maximum current Amperage					kA				
95		Maximum current density per rectifier					A/m <sup>2</sup>				
96		Cell voltage					V				
97		Total cell voltage per rectifier					V				
98		Bus-bar and losses voltage					V				
99		Total voltage per rectifier					V				
100		Operating power per rectifier					kW				
101		Number of stripping machines									
102		Stripping method									
103		Capacity of stripping machine					Cathodes/hr				
104		Weight of one side copper deposit					kg				
105											

There are many reasons which will guide designer to take a one option such as the cost of the big rectifier, the electrical arrangement... At this level the second option is taken. The design number of cells into the cell house is changed from “158” to “160”.

- In the excel cell “F77” (design number of cells per cell house), type number “160”.
- In the excel cell “F78”, the number of cell-house cathode becomes “11040”
- In the excel cell “F79”, the number of unloaded cathodes per day becomes “1577.14”.
- In the excel cell “F81”, the number of crane revolutions per day becomes “68.57”.
- In the excel cell “F83”, the number of crane revolutions per day and per crane becomes “34.29”.
- In the excel cell “F85”, the number of cells per rectifier becomes “80”.
- In the excel cell “F86”, the number of cells per block becomes “40”.
- In the excel cell “F88” (operating current density), type “=F73/(F59\*F56\*F78\*F58\*10^-6)” (mathematical expression 6).

The value of operating current density is close to the value of design current density.

## 2. Calculation of copper electrolyte flow parameters

### • Spent electrolyte flow

The known parameters of the spent electrolyte flow are:

- Spent electrolyte copper tenor
  - Spent electrolyte iron tenor
  - Spent electrolyte acid tenor
- In the excel cell “D14” (spent electrolyte copper tenor), type “=F64”.
  - In the excel cell “D15” (spent electrolyte iron tenor), type “=F67”.
  - In the excel cell “D16” (spent electrolyte acid tenor), type “=F65”.
  - In the excel cell “D13” (spent electrolyte total salt tenor), type “=D14\*F62+D15\*F63+D16\*F61”.
  - In the excel cell “D11” (spent electrolyte liquid SG), type “=(-6.139\*10^-4\*D13^2+0.9742\*D13+1000)/1000”.

The liquid volume flowrate of spent electrolyte is an unknown parameter and it becomes a solver variable. The starting value of liquid volume flowrate is “100”.

- In the excel cell “D10”, type number “100” (blue color).
- In the excel cell “D9” (spent electrolyte liquid mass flowrate), type “=D10\*D11”.
- In the excel cell “D18” (spent electrolyte copper mass flowrate), type “=D10\*D14”.
- In the excel cell “D19” (spent electrolyte iron mass flowrate), type “=D10\*D15”.
- In the excel cell “D20” (spent electrolyte acid mass flowrate), type “=D10\*D16”.

### • Iron bleed flow

The known parameters of the iron bleed flow are:

- Iron bleed copper tenor
  - Iron bleed iron tenor
  - Iron bleed acid tenor
- In the excel cell “I34” (iron bleed copper tenor), type “=D14”.
  - In the excel cell “I35” (iron bleed iron tenor), type “=D15”.

- In the excel cell “**I36**” (iron bleed acid tenor), type “=**D16**”.
- In the excel cell “**I33**” (iron bleed total salt tenor), type “=**I34\*F62+I35\*F63+I36\*F61**”.
- In the excel cell “**I31**” (iron bleed liquid SG), type “=**(-6.139\*10^-4\*I33^2+0.9742\*I33+1000)/1000**”.

The ratio of iron bleed flowrate/spent electrolyte flowrate is an unknown value and it becomes a solver variable. The starting value of the ratio of iron bleed flowrate/spent electrolyte flowrate is “**1.00**”.

- In the excel cell “**F43**”, type a number “**1.00**” (blue color).
- In the excel cell “**I30**” (iron bleed liquid volume flowrate), type “=**D10\*F43/100**”.
- In the excel cell “**I29**” (iron bleed liquid mass flowrate), type “=**I30\*I31**”.
- In the excel cell “**I38**” (iron bleed copper mass flowrate), type “=**I30\*I34**”.
- In the excel cell “**I39**” (iron bleed iron mass flowrate), type “=**I30\*I35**”.
- In the excel cell “**I40**” (iron bleed acid mass flowrate), type “=**I30\*I36**”.

- Advance electrolyte flow

The known parameter of the advance electrolyte flow is:

- Advance electrolyte copper tenor

- In the excel cell “**E14**” (advance electrolyte copper tenor), type “=**F66**”.
- In the excel cell “**E18**” (advance electrolyte copper mass flowrate), type “=**D18+I38+F73\*1000**”.
- In the excel cell “**E19**” (advance electrolyte iron mass flowrate), type “=**D19+(E18-D18)/F68**”.

Assuming that iron is transported into the copper electrowinning circuit only by the chemical transfer way. In consequence all transferred iron are iron III.

- In the excel cell “**E20**” (advance electrolyte acid mass flowrate), type “=**D20+(D18-E18)\*98/63.55+(D19-E19)\*3\*98/(2\*55.85)**” where 98, 63.55 and 55.85 are the molar masses of acid, copper and iron.
- In the excel cell “**E10**” (advance electrolyte liquid volume flowrate), type “=**E18/E14**”.
- In the excel cell “**E15**” (advance electrolyte iron tenor), type “=**E19/E10**”.
- In the excel cell “**E16**” (advance electrolyte acid tenor), type “=**E20/E10**”.
- In the excel cell “**E13**” (advance electrolyte total salt tenor), type “=**E14\*F62+E15\*F63+E16\*F61**”.
- In the excel cell “**E11**” (advance electrolyte SG), type “=**(-6.139\*10^-4\*E13^2+0.9742\*E13+1000)/1000**”.
- In the excel cell “**E9**” (advance electrolyte liquid mass flowrate), type “=**E10\*E11**”.

- Solver set objective and constraint 1

- In the excel cell “**D46**” (solver set objective), type “=**D9+(E18-D18)/1000+(E19-D19)/1000+(E20-D20)/1000\*2/98-E9**” where 2 and 98 are molar masses of two hydrogen atoms and acid. The color of number into the excel cell “**D46**” is green.

At this level, the value of acid tenor of the advance electrolyte is “**20.67**”. This is far from the values usually found into the existing plants. The value of liquid volume flowrate of spent electrolyte must be change manually until the value of acid tenor of the advance electrolyte is greater than “**150**”.

- In the excel cell “**D10**”, the number is changed from “100” to “**550**”.

The value of acid tenor of the advance electrolyte changes from “**20.67**” to “**153.83**”.

- In the excel cell “**D47**” (constraint 1), type “=**E19-D19-I39**”. The color of number into the excel cell “**D47**” is green.

- Copper cathode solid mass flowrate of scavenger circuit

- In the excel cell “**F89**” (electrolyte flowrate per cell), type “=**F60**\***F56**\***F75**”.
- In the excel cell “**F90**” (number of cells into the scavenger circuit), type “=**E10**/**F89**”.
- In the excel cell “**F91**” (design number of cells into the scavenger circuit), type “=**ROUNDUP**(**F90**,0)”.
- In the excel cell “**F6**” (copper cathode solid mass flowrate), type “=**F59**\***F56**\***F88**\***F91**\***F75**\***F58**\*10<sup>-6</sup>”.

- Oxygen gas mass flowrate of scavenger circuit

- In the excel cell “**G7**” (oxygen gas mass flowrate), type “=**F6**\*16/63.55” where 16 and 63.55 are the atomic masses of oxygen and copper.

- Scavenger electrolyte flow

- In the excel cell “**H9**” (scavenger electrolyte liquid mass flowrate), type “=**E9**-**F6**-**G7**”.
- In the excel cell “**H18**” (scavenger electrolyte copper mass flowrate), type “=**E18**-**F6**\*1000”.
- In the excel cell “**H19**” (scavenger electrolyte iron mass flowrate), type “=**E19**”.
- In the excel cell “**H20**” (scavenger electrolyte acid mass flowrate), type “=**E20**+(**E18**-**H18**)\*98/63.55” where 98 and 63.55 are molar masses of acid and copper.

The scavenger electrolyte liquid volume flowrate is an unknown parameter and it is a solver variable. The starting value of scavenger electrolyte liquid volume flowrate is the value of advance electrolyte liquid volume flowrate.

- In the cell “**H10**”, type “**557.08**” (blue color).
- In the excel cell “**H14**” (scavenger electrolyte copper tenor), type “=**H18**/**H10**”.
- In the excel cell “**H15**” (scavenger electrolyte iron tenor), type “=**H19**/**H10**”.
- In the excel cell “**H16**” (scavenger electrolyte acid tenor), type “=**H20**/**H10**”.
- In the excel cell “**H13**” (scavenger electrolyte total salt tenor), type “=**H14**\***F62**+**H15**\***F63**+**H16**\***F61**”.
- In the excel cell “**H11**” (scavenger electrolyte SG), type “=**(-6.139**\*10<sup>-4</sup>\***H13**<sup>2</sup>+0.9742\***H13**+1000)/1000”.

- Solver constraint 2

- In the excel cell “**D48**” (solver constraint 2), type “=**H9**-**H10**\***H11**”. The color of number into the excel cell “**D48**” is g

- Feed commercial flow

- In the excel cell “**F92**” (number of cells of commercial circuit), type “=**F77**-**F91**”.
- In the excel cell “**E30**” (feed commercial electrolyte liquid volume flowrate), type “=**F92**\***F89**”.

The feed commercial electrolyte copper, iron, and acid tenors are unknown parameters. They are solver variables. The starting values of feed commercial electrolyte copper, iron, and acid tenors are the values of scavenger electrolyte copper, iron, and acid tenors.

- In the excel cell “**E34**” (feed commercial electrolyte copper tenor), type number “**47.36**” (blue color).
- In the excel cell “**E35**” (feed commercial electrolyte iron tenor), type number “**2.00**” (blue color).
- In the excel cell “**E36**” (feed commercial electrolyte acid tenor), type number “**157.90**” (blue color).
- In the excel cell “**E33**” (feed commercial electrolyte total salt tenor), type “=**E34**\***F62**+**E35**\***F63**+**E36**\***F61**”.
- In the excel cell “**E31**” (feed commercial electrolyte SG), type “=**(-6.139**\*10<sup>-4</sup>\***E33**<sup>2</sup>+0.9742\***E33**+1000)/1000”.

- In the excel cell “E29” (feed commercial electrolyte liquid mass flowrate), type “=E30\*E31”.
  - In the excel cell “E38” (feed commercial electrolyte copper mass flowrate), type “=E30\*E34”.
  - In the excel cell “E39” (feed commercial electrolyte iron mass flowrate), type “=E30\*E35”.
  - In the excel cell “E40” (feed commercial electrolyte acid mass flowrate), type “=E30\*E36”.
- Copper cathode solid mass flowrate of commercial circuit
- In the excel cell “F26” (copper cathode solid mass flowrate), type “=F73-F6”.
- Oxygen gas mass flowrate of commercial circuit
- In the excel cell “G27” (oxygen gas mass flowrate), type “=F26\*16/63.55” where 16 and 63.55 are the atomic masses of oxygen and copper.
- Out commercial electrolyte

The known parameters of the out commercial electrolyte flow are:

- Out commercial electrolyte copper tenor
  - Out commercial electrolyte iron tenor
  - Out commercial electrolyte acid tenor
- In the excel cell “H34” (out commercial electrolyte copper tenor), type “=I34”.
  - In the excel cell “H35” (out commercial electrolyte iron tenor), type “=I35”.
  - In the excel cell “H36” (out commercial electrolyte acid tenor), type “=I36”.
  - In the excel cell “H33” (out commercial electrolyte total salt tenor), type “=H34\*F62+H35\*F63+H36\*F61”.
  - In the excel cell “H31” (out commercial electrolyte SG), type “=(-6.139\*10^-4\*H33^2 +0.9742\*H33 +1000)/1000”.
  - In the excel cell “H29” (out commercial electrolyte liquid mass flowrate), type “=E29-F26-G27”.
  - In the excel cell “H30” (out commercial electrolyte liquid volume flowrate), type “=H29/H31”.
  - In the excel cell “H38” (out commercial electrolyte copper mass flowrate), type “=E38-F26\*1000”.
  - In the excel cell “H39” (out commercial electrolyte iron mass flowrate), type “=E39”.
  - In the excel cell “H40” (feed commercial electrolyte acid mass flowrate), type “=E40+(E38-H38)\*98/63.55”.

Solver constraints 3, 4 and 5

- In the excel cell “D49” (solver constraint 3), type “=H38/H30-H34”. The color of number into the excel cell “D49” is green.
- In the excel cell “D50” (solver constraint 4), type “=H39/H30-H35”. The color of number into the excel cell “D50” is green.
- In the excel cell “G46” (solver constraint 5), type “=H40/H30-H36”. The color of number into the excel cell “G46” is green.

- Recycle electrolyte

The known parameters of the recycle electrolyte flow are:

- Recycle electrolyte copper tenor
- Recycle electrolyte iron tenor
- Recycle electrolyte acid tenor

- In the excel cell “I14” (recycle electrolyte copper tenor), type “=I34”.
- In the excel cell “I15” (recycle electrolyte iron tenor), type “=I35”.
- In the excel cell “I16” (recycle electrolyte acid tenor), type “=I36”.
- In the excel cell “I13” (recycle electrolyte total salt tenor), type “=I14\*F62+I15\*F63+I16\*F61”.
- In the excel cell “I11” (recycle electrolyte SG), type “=(-6.139\*10^-4\*I13^2 +0.9742\*I13 +1000)/1000”.
- In the excel cell “I9” (recycle electrolyte liquid mass flowrate), type “=H29-I29-D9”.
- In the excel cell “I10” (recycle electrolyte liquid volume flowrate), type “=I9/I11”.
- In the excel cell “I18” (recycle electrolyte copper mass flowrate), type “=I10\*I14”.
- In the excel cell “I19” (recycle electrolyte iron mass flowrate), type “=I10\*I15”.
- In the excel cell “I20” (recycle electrolyte acid mass flowrate), type “=I10\*I16”.

- Acid flow

The known parameter of the acid flow is:

- Acid SG

- In the excel cell “D31” (acid SG), type number “1.84”.
- In the excel cell “D40” (acid flow acid mass flowrate), type “=E40-I20-H20”.
- In the excel cell “D29” (acid flow liquid mass flowrate), type “=(D40/0.98)/1000” where 0.98 is mass fraction (w/w) of pure acid into the industrial acid.
- In the excel cell “D30” (acid flow liquid volume flowrate), type “=D29/D31”.

- Water flow

The known parameter of the water flow is:

- Water SG

- In the excel cell “J11” (water SG), type number “1.000”.
- In the excel cell “J9” (water liquid mass flowrate), type “=E29-D29-I9-H9”.
- In the excel cell “J10” (water liquid volume flowrate), type “=J9/J11”.

At this level, it appears Table 10 as it appears on Excel Microsoft spreadsheet. Table 10 gives simulation results of copper electrowinning circuit with the starting values of solver variables. Simulation results are not optimized. Excel solver program will be used for the optimization.

### 3. Excel solver program

Excel solver program execution is as follows:

- 1) On the ‘Data’, in the ‘Analysis group’ click **solver** (if the solver command is not available, you must activate the solver add-in).
- 2) In the ‘Set objective’ box, enter the cell reference ‘D46’ of simulation solver constraint table..
- 3) Click ‘Value of’ and then type the number ‘0’ in the box.
- 4) In the ‘By Changing Variable Cells’ box, enter the reference for each solver variable (blue color in Table 10 and simulation variable table). Separate the references with commas (English version).
- 5) In the ‘Subject to the constraints’ box, enter solver constraints by doing the following:
  - a. In the ‘Solver Parameters’ dialog box, click ‘Add’.
  - b. In the ‘Cell Reference’ box, enter the cell reference of constraint 1 (simulation solver constraint table).
  - c. Click the ‘relationship’ ‘=’, in the ‘Constraint’ box, type the number ‘0’.
  - d. Click ‘Add’ for the second solver constraint. When the last solver constraint is added (cell ‘G46’), click ‘OK’ to return to ‘Solver Parameters’ dialog box.

	A	B	C	D	E	F	G	H	I	J	K	
1												
2		<b>Table</b>	<b>10A</b>	<b>Simulation table of copper electrowinning circuit</b>								
3												
4				1	2	3	4	5	6	7		
5		Designation		Sp El	Ad El	Sc CC	ScOx	ScEl	Re El	Water		
6		Solid mass	t/h			1.472						
7		Gas Mass	t/h				0.371					
8		Liquid										
9		Mass	t/h	671.2	683.9			682.1	2542.9	52.62		
10		Volume	m <sup>3</sup> /h	550.0	557.1			557.1	2083.6	52.62		
11		SG	t/m <sup>3</sup>	1.220	1.228			1.226	1.220	1.000		
12												
13		$C_t^s$	g/l	273.32	284.82			282.26	273.32			
14		Cu	g/l	35.00	50.0			47.36	35.00			
15		Fe	g/l	2.00	2.00			2.00	2.00			
16		Acid	g/l	180.00	153.83			157.90	180.00			
17												
18		Cu	Kg/h	19250.0	27853.9			26381.9	72926.9			
19		Fe	Kg/h	1100.0	1114.3			1114.3	4167.3			
20		Acid	Kg/h	99000.0	85694.2			87964.2	375052.8			
21												
22		<b>Table</b>	<b>10B</b>	<b>Simulation table of copper electrowinning circuit</b>								
23												
24				8	9	10	11	12	13			
25		Designation		Acid	FCoEl	CoCC	CoOx	CoEl	FeBl			
26		Solid Mass	t/h			6.939						
27		Gas Mass	t/h				1.747					
28		Liquid										
29		Mass	t/h	-48.06	3229.5			3220.8	6.71			
30		Volume	m <sup>3</sup> /h	-26.12	2634.0			2639.1	5.50			
31		SG	t/m <sup>3</sup>	1.840	1.226			1.220	1.220			
32												
33		$C_t^s$	g/l		282.26			273.32	273.32			
34		Cu	g/l		47.36			35.00	35.00			
35		Fe	g/l		2.00			2.00	2.00			
36		Acid	g/l		157.90			180.00	180.00			
37												
38		Cu	Kg/h		124747.8			117808.4	192.50			
39		Fe	Kg/h		5268.1			5268.1	11.00			
40		Acid	Kg/h	-47103.1	415913.9			426615.2	990.00			
41												
42		<b>Simulation additional solver variable table</b>										
43		Fe bleed flowrate/spent electrolyte flowrate				1.00		%				
44												
45		<b>Simulation solver constraint table</b>										
46		Set objective		-4.336	Constraint 5		-18.350					
47		Constraint 1		3.340								
48		Constraint 2		-0.951								
49		Constraint 3		9.639								
50		Constraint 4		-0.004								
51												

	A	B	C	D	E	F	G	H	I	J	K
52	<b>Simulation table data</b>										
53	Production rate					<b>70,000</b>	t/y				
54	Working hours per year					<b>8,322</b>	hrs				
55	Type of cathode blank					<b>Kidd</b>					
56	Cathode active area					<b>2.32</b>	m <sup>2</sup>				
57	Design current density					<b>300</b>	A/m <sup>2</sup>				
58	Current efficiency					<b>0.9</b>					
59	Constant k					<b>1.1858</b>	g/A-Hr				
60	Cathode face velocity					<b>0.12</b>	(m <sup>3</sup> /h/m <sup>2</sup> )				
61	Constant $\alpha_1$ (acid)					<b>1.000</b>					
62	Constant $\alpha_2$ (copper)					<b>2.511</b>					
63	Constant $\alpha_4$ (iron)					<b>2.719</b>					
64	Spent electrolyte copper tenor					<b>35</b>	g/l				
65	Spent electrolyte acid tenor					<b>180</b>	g/l				
66	Advance electrolyte copper tenor					<b>50</b>	g/l				
67	Spent electrolyte iron tenor					<b>2</b>	g/l				
68	Ratio of stripped Cu on Stripped Fe from SX					<b>600</b>					
69	Harvest cycle					<b>7</b>	days				
70	Stripping machine working hours per day					<b>19</b>	hrs				
71											
72	<b>Simulation table results</b>										
73	Design production rate					8.411	t/h				
74	Number of cell-house cathodes					10901.7					
75	Number of cathodes per cell					<b>69</b>					
76	Number of cells per cell-house					158					
77	Design number of cells per cell-house					<b>160</b>					
78	Design number of cell-house cathodes					11040					
79	Number of unloaded cathodes per day					1577.1					
80	Number of unloaded cathodes per crane					23					
81	Number of crane revolutions per day					68.57					
82	Number of cranes					<b>2</b>					
83	Number of crane revolutions/day per crane					34.29					
84	Number of rectifier					<b>2</b>					
85	Number of cells per rectifier					80					
86	Number of cells per block					40					
87	Number of blocks per cell-house					4					
88	Operating current density					296.24	A/m <sup>2</sup>				
89	Electrolyte flowrate per cell					19.95	m <sup>3</sup> /h				
90	Number of cells/scavenger					27.92					
91	Design number of cells/scavenger					28					
92	Number of cells/commercial					132					
93	Operating current Amperage						kA				
94	Maximum current Amperage						kA				
95	Maximum current density per rectifier						A/m <sup>2</sup>				
96	Cell voltage						V				
97	Total cell voltage per rectifier						V				
98	Bus-bar and losses voltage						V				
99	Total voltage per rectifier						V				
100	Operating power per rectifier						kW				
101	Number of stripping machines										
102	Stripping method										
103	Capacity of stripping machine						Cathodes/hr				
104	Weight of one side copper deposit						kg				
105											

	A	B	C	D	E	F	G	H	I	J	K
1											
2		<b>Table</b>	<b>11A</b>	<b>Simulation table of copper electrowinning circuit</b>							
3											
4				1	2	3	4	5	6	7	
5		Designation		Sp El	Ad El	Sc CC	ScOx	ScEl	Re El	Water	
6		Solid mass	t/h			1.525					
7		Gas Mass	t/h				0.384				
8		Liquid									
9		Mass	t/h	692.8	701.3			699.3	2483.5	9.17	
10		Volume	m <sup>3</sup> /h	567.7	570.7			569.7	2035.0	9.17	
11		SG	t/m <sup>3</sup>	1.220	1.229			1.227	1.220	1.000	
12											
13		$C_t^s$	g/l	273.32	286.61			284.29	273.32		
14		Cu	g/l	35.00	50.00			47.41	35.00		
15		Fe	g/l	2.00	2.01			2.02	2.00		
16		Acid	g/l	180.00	155.58			159.97	180.00		
17											
18		Cu	Kg/h	19869.9	28534.1			27009.5	71224.0		
19		Fe	Kg/h	1135.4	1149.9			1149.9	4069.9		
20		Acid	Kg/h	102188.3	88789.4			91140.4	366294.7		
21											
22		<b>Table</b>	<b>11B</b>	<b>Simulation table of copper electrowinning circuit</b>							
23											
24				8	9	10	11	12	13		
25		Designation		Acid	FCoEl	CoCC	CoOx	CoEl	FeBl		
26		Solid Mass	t/h			6.887					
27		Gas Mass	t/h				1.734				
28		Liquid									
29		Mass	t/h	1.76	3193.8			3185.2	8.81		
30		Volume	m <sup>3</sup> /h	0.96	2614.1			2609.9	7.32		
31		SG	t/m <sup>3</sup>	1.840	1.222			1.220	1.220		
32											
33		$C_t^s$	g/l		275.44			273.32	273.32		
34		Cu	g/l		37.58			35.00	35.00		
35		Fe	g/l		2.00			2.00	2.00		
36		Acid	g/l		175.65			180.00	180.00		
37											
38		Cu	Kg/h		98233.5			91346.6	252.7		
39		Fe	Kg/h		5219.8			5219.8	14.4		
40		Acid	Kg/h	1727.3	459162.5			469782.7	1299.6		
41											
42		<b>Simulation additional solver variable table</b>									
43		Fe bleed flowrate/spent electrolyte flowrate				1.27	%				
44											
45		<b>Simulation solver constraint table</b>									
46		Set objective	0.000	Constraint 5			0.000				
47		Constraint 1	0.000								
48		Constraint 2	0.000								
49		Constraint 3	0.000								
50		Constraint 4	0.000								
51											

	A	B	C	D	E	F	G	H	I	J	K
52	<b>Simulation table data</b>										
53	Production rate					<b>70,000</b>	t/y				
54	Working hours per year					<b>8,322</b>	hrs				
55	Type of cathode blank					<b>Kidd</b>					
56	Cathode active area					<b>2.32</b>	m <sup>2</sup>				
57	Design current density					<b>300</b>	A/m <sup>2</sup>				
58	Current efficiency					<b>0.9</b>					
59	Constant k					<b>1.1858</b>	g/A-Hr				
60	Cathode face velocity					<b>0.12</b>	(m <sup>3</sup> /h/m <sup>2</sup> )				
61	Constant $\alpha_1$ (acid)					<b>1.000</b>					
62	Constant $\alpha_2$ (copper)					<b>2.511</b>					
63	Constant $\alpha_4$ (iron)					<b>2.719</b>					
64	Spent electrolyte copper tenor					<b>35</b>	g/l				
65	Spent electrolyte acid tenor					<b>180</b>	g/l				
66	Advance electrolyte copper tenor					<b>50</b>	g/l				
67	Spent electrolyte iron tenor					<b>2</b>	g/l				
68	Ratio of stripped Cu on Stripped Fe from SX					<b>600</b>					
69	Harvest cycle					<b>7</b>	days				
70	Stripping machine working hours per day					<b>19</b>	hrs				
71											
72	<b>Simulation table results</b>										
73	Design production rate					8.411	t/h				
74	Number of cell-house cathodes					10901.7					
75	Number of cathodes per cell					69					
76	Number of cells per cell-house					158					
77	Design number of cells per cell-house					160					
78	Design number of cell-house cathodes					11040					
79	Number of unloaded cathodes per day					1577.1					
80	Number of unloaded cathodes per crane					23					
81	Number of crane revolutions per day					68.57					
82	Number of cranes					2					
83	Number of crane revolutions/day per crane					34.29					
84	Number of rectifier					2					
85	Number of cells per rectifier					80					
86	Number of cells per block					40					
87	Number of blocks per cell-house					4					
88	Operating current density					296.24	A/m <sup>2</sup>				
89	Electrolyte flowrate per cell					19.95	m <sup>3</sup> /h				
90	Number of cells/scavenger					28.60					
91	Design number of cells/scavenger					29					
92	Number of cells/commercial					131					
93	Operating current Amperage					49.26	kA				
94	Maximum current Amperage					65.68	kA				
95	Maximum current density per rectifier					394.99	A/m <sup>2</sup>				
96	Cell voltage					2.12	V				
97	Total cell voltage per rectifier					169.21	V				
98	Bus-bar and losses voltage					25.38	V				
99	Total voltage per rectifier					194.59	V				
100	Operating power per rectifier					9585.69	kW				
101	Number of stripping machines					2					
102	Stripping method					Manual					
103	Capacity of stripping machine					41.50	Cathodes/hr				
104	Weight of one side copper deposit					64.00	kg				
105											

- 6) Click ‘**Solve**’. To keep the solution values on the worksheet, in the ‘**Solver Results**’ dialog box, click ‘**Keep solver solution**’.

At this level, it appears Table 11 as it appears on Excel Microsoft spreadsheet. Table 11 gives optimized simulation results of copper electrowinning circuit.

#### 4. Calculation of other parameters

- In the excel cell “**F93**” (operating current amperage), type “=**F88**\***F75**\***F56**/1000”.
- In the excel cell “**F94**” (maximum DC current amperage of rectifier), type “=**F93**/0.75”.
- In the excel cell “**F95**” (maximum current density of rectifier), type “=**F88**/0.75”.
- In the excel cell “**F96**” (cell voltage), type “=(1.57+7.69\*10<sup>-4</sup>\***F88**)/(1-0.15)”.
- In the excel cell “**F97**” (Total cell voltage per rectifier), type “=**F96**\***F85**”.
- In the excel cell “**F98**” (Bus-bar and losses voltage), type “=**F97**\*15/100”.
- In the excel cell “**F99**” (Total rectifier voltage), type “=**F97**+**F98**”.
- In the excel cell “**F100**” (Operating power per rectifier), type “=**F99**\***F93**”.

The number of the stripping machine is 2 to have 2 machines (capacity 60 cathodes/hour).

- In the excel cell “**F101**” (number of stripping machines), type number “2”.
- In the excel cell “**F102**” (stripping method), type “**semi-manual**”.
- In the excel cell “**F103**” (stripping machine capacity), type “=(**F78**/**F101**)/(**F69**\***F70**)”.
- In the excel cell “**F104**” (maximum weight of one side copper), type “=**F59**\***F56**\***F88**\***F58**\***F69**\*12\*10<sup>-3</sup>”.

### 5.3.2. Existing copper electrowinning circuit

#### 5.3.2.1. Additional notions

The existing copper electrowinning circuit will be simulated to have the operating current density for a given transferred copper rate. The transferred copper rate is the quantity by unit of time which copper electrowinning receives from one or more copper solvent extraction circuits. In the case of the transferred copper come from one copper solvent extraction, the copper transferred to the copper solvent circuit can come from one or more pregnant leach solution (PLS).

The mathematical expression (42) gives the transferred copper to the copper electrowinning circuit.

$$\text{Transferred copper rate (t/h)} = \sum_{\beta=1}^t V_{\beta} \times (C_{\beta}^P - C_{\beta}^R) \quad (42)$$

Where “ $\beta$ ” is the number of PLS flows which transfer copper to the copper electrowinning circuit ( $\beta$  varies from 1 to  $t$ ), “ $V_{\beta}$ ” is the flowrate of PLS of rank  $\beta$  ( $m^3/h$ ), “ $C_{\beta}^P$ ” is the copper tenor into the PLS of rank  $\beta$  ( $g/l$ ), and “ $C_{\beta}^R$ ” is copper tenor into the raffinate of rank  $\beta$  ( $g/l$ ).

The maximum operating current density is given by the mathematical expression (43).

$$\text{MOCD} = \text{MCD} \times 0.95 \quad (43)$$

Where “MOCD” is the maximum operating current density ( $A/m^2$ ), and “MCD” is the maximum current density ( $A/m^2$ ).

The maximum copper production rate is given by the mathematical expression (44).

$$\text{MPR} = K \times A \times n \times \text{MOCD} \times \eta \times 10^{-6} \quad (44)$$

Where “MPR” is maximum copper production rate (t/h), “K” is a constant (1.18576 grams of copper deposited per amp-hour), “A” is cathode active area (m<sup>2</sup>), “n” is the number of cathodes into the cell-house, “MOCD” is operating current density (A/m<sup>2</sup>), and “η” is current efficiency.

The maximum transferred copper rate is given the mathematical expression (45).

$$\text{MTR} = \frac{\text{MPR}}{1-\gamma} \quad (45)$$

Where “MTR” is the maximum transferred copper rate (t/h), “MPR” is the maximum copper production rate (t/h), and “γ” is a constant.

The value of the constant γ is given by the mathematical expression (46).

$$\gamma = \frac{\text{MOCD}}{\alpha \times C_{\text{Fe}} \times \mu} \quad (46)$$

Where “γ” is a constant, “MOCD” is the maximum operating current density, “α” is the ratio of the stripped copper on the stripped iron from copper solvent extraction circuit, “C<sub>Fe</sub>” is the iron tenor into the iron bleed, “μ” is the ratio of the maximum operating current density on the spent electrolyte copper tenor.

### 5.3.2.2. Design data

The existing copper electrowinning circuit is the copper electrowinning circuit which has been designed in paragraph (5.3.1.). The existing copper electrowinning circuit will be simulated to have the operating current density for a given transferred rate. Table 12 gives design data of the existing copper electrowinning circuit.

The simulation table of copper electrowinning circuit is given by Table 13 as it appears on the Excel spreadsheet. Table 13 is accompanied by 4 small tables:

- Simulation additional solver variable table: Simulation additional solver variable gives the value of solver variables which are not into Table 13.
- Simulation solver constraint table: Simulation solver constraint table gives solver constraints which will be used in the solver program.
- Simulation data table: Simulation data table gives data of copper electrowinning circuit which are in Table 12. The color of number in the simulation data table is red.
- Simulation result table: Simulation result table gives the number and size of major equipment.

In Table 13, each column gives the copper electrowinning flow as it appears on Figure 4. Each line gives flow parameters. Abbreviations mean:

- SpEl : Spent electrolyte
- AdEl : Advance electrolyte
- ScCC : Scavenger copper cathode
- ScOx : Scavenger oxygen
- ScEl : Scavenger electrolyte
- ReEl : Recycle electrolyte
- FCoEl: Feed commercial electrolyte
- CoCC: Commercial copper cathode
- CoOx: Commercial oxygen
- CoEl : Commercial electrolyte
- FeBl : Iron bleed

Table 12: Design data of copper electrowinning circuit

Designation		Unit
Maximum DC amperage of rectifier	65.68	kA
Maximum current density of rectifier	395	A/m <sup>2</sup>
Maximum operating density	375.25	A/m <sup>2</sup>
Spent electrolyte iron tenor	1	g/l
Ratio of stripped copper on stripped iron from SX	600	
Ratio of Maximum operating current on spent electrolyte copper tenor	9	
Working hours per year	8322	hrs
Type of cathode blank	ISA	
Cathode active area	2.41	m <sup>2</sup>
Current efficiency	0.90	
Constant K	1.1858	g/Amp-hour
Design spent electrolyte volume flowrate	567.71	m <sup>3</sup> /h
Cathode face velocity	0.12	(m <sup>3</sup> /h)/m <sup>2</sup>
Constant $\alpha_1$ (acid)	1.000	
Constant $\alpha_2$ (copper)	2.511	
Constant $\alpha_4$ (iron)	2.719	
Spent electrolyte acid tenor	180	g/l
Number of cathodes per cell	69	
Number of cells per cell house	160	
Number of cells into the scavenger circuit	29	
Number of cranes	2	
Number of rectifiers	2	
Number of stripping machines	2	
Spent electrolyte acid tenor	190	g/l
Stripping method	Semi-manual	
Stripping machine working hours per day	19	hours
Weight of one side copper deposit	60	kg

### 5.3.2.3. Simulation procedure of the existing copper electrowinning circuit

The simulation procedure of the existing copper electrowinning circuit is as follow:

1. *Calculation of maximum copper production rate, maximum transferred copper rate, and copper production rate*

- In the excel cell “F82” (number of cathodes into the cell house), type “=F71\*F72”.
- In the excel cell “F83” (maximum copper production rate –t/h), type “=F64\*F62\*F56\*F82\*F63\*10<sup>-6</sup>”.

	A	B	C	D	E	F	G	H	I	J	K
1											
2		<b>Table</b>	<b>13A</b>	<b>Simulation table of copper electrowinning circuit</b>							
3											
4				1	2	3	4	5	6	7	
5		Designation		Sp El	Ad El	Sc CC	ScOx	ScEl	Re El	Water	
6		Solid mass	t/h								
7		Gas Mass	t/h								
8		Liquid									
9		Mass	t/h								
10		Volume	m <sup>3</sup> /h								
11		SG	t/m <sup>3</sup>								
12											
13		$C_t^s$	g/l								
14		Cu	g/l								
15		Fe	g/l								
16		Acid	g/l								
17											
18		Cu	Kg/h								
19		Fe	Kg/h								
20		Acid	Kg/h								
21											
22		<b>Table</b>	<b>13B</b>	<b>Simulation table of copper electrowinning circuit</b>							
23											
24				8	9	10	11	12	13		
25		Designation		Acid	FCoEl	CoCC	CoOx	CoEl	FeBl		
26		Solid Mass	t/h								
27		Gas Mass	t/h								
28		Liquid									
29		Mass	t/h								
30		Volume	m <sup>3</sup> /h								
31		SG	t/m <sup>3</sup>								
32											
33		$C_t^s$	g/l								
34		Cu	g/l								
35		Fe	g/l								
36		Acid	g/l								
37											
38		Cu	Kg/h								
39		Fe	Kg/h								
40		Acid	Kg/h								
41											
42		<b>Simulation additional solver variable table</b>									
43		Fe bleed flowrate/spent electrolyte flowrate						%			
44		Operating current density						A/m <sup>2</sup>			
45											
46		<b>Simulation solver constraint table</b>									
47		Set objective				Constraint 5					
48		Constraint 1				Constraint 6					
49		Constraint 2									
50		Constraint 3									
51		Constraint 4									
52											

	A	B	C	D	E	F	G	H	I	J	K	
53	<b>Simulation table data</b>											
54		Maximum current amperage of rectifier				<b>65.68</b>	KA					
55		Maximum current density of rectifier				<b>395</b>	A/m <sup>2</sup>					
56		Maximum operating current density				<b>375.25</b>	A/m <sup>2</sup>					
57		Spent electrolyte iron tenor				<b>1.00</b>	g/l					
58		Ratio of stripped Cu on stripped Fe				<b>600</b>						
59		Ratio of OCD on spent electrolyte copper tenor				<b>9.7</b>						
60		Working hours per year				<b>8322</b>	hrs					
61		Type of cathode blank				<b>ISA</b>						
62		Cathode active area				<b>2.41</b>	m <sup>2</sup>					
63		Current efficiency				<b>0.9</b>						
64		Constant K				<b>1.1858</b>	g/A-hrs					
65		Design spent electrolyte flowrate				<b>567.71</b>	m <sup>3</sup> /h					
66		Cathode face velocity				<b>0.12</b>	m <sup>3</sup> /h/m <sup>2</sup>					
67		Constant $\alpha_1$ (acid)				<b>1.000</b>						
68		Constant $\alpha_2$ (copper)				<b>2.511</b>						
69		Constant $\alpha_4$ (iron)				<b>2.719</b>						
70		Spent electrolyte acid tenor				<b>180</b>	g/l					
71		Number of cathodes per cell				<b>69</b>						
72		Number of cells per cell house				<b>160</b>						
73		Number of cells/scavenger circuit				<b>29</b>						
74		Number of cranes				<b>2</b>						
75		Number of rectifiers				<b>2</b>						
76		Number of stripping machines				<b>2</b>						
77		Stripping method				<b>manual</b>						
78		Stripping machine working hours/day				<b>19</b>	hrs					
79		Weight of one side copper deposit				<b>60</b>	kg					
80												
81	<b>Simulation table results</b>											
82		Number of cathodes/cell house										
83		Maximum production rate					t/h					
84		Maximum transferred copper rate					t/h					
85		Transferred copper rate					t/h					
86		Production rate					t/h					
87		Production rate					h/y					
88		Spent electrolyte copper tenor					g/l					
89		Electrolyte flowrate per cell/scavenger					m <sup>3</sup> /h					
90		Cathode face velocity/scavenger					(m <sup>3</sup> /h)/m <sup>2</sup>					
91		Electrolyte flowrate per cell/commercial					m <sup>3</sup> /h					
92		Number of cells/commercial										
93		Harvest cycle					days					
94		Operating harvest cycle					days					
95		Number of unloaded cathodes/day										
96		Number of unloaded cathodes/crane										
97		Number of crane revolutions/day										
98		Number of crane revolution/day/crane										
99		Number of cells/rectifier										
100		Cell voltage					V					
101		Total cell voltage per rectifier					V					
102		Bus-bar and losses voltage					V					
103		Total rectifier voltage					V					
104		Operating current amperage					kA					
105		Operating rectifier power					kW					
106		Capacity of stripping machine					Cathodes/h					
107												

- In the excel cell “**F84**” (maximum transferred copper rate), type “ $=F83/(1-F56/(F58*F57*F59))$ ”.

The transferred copper rate must be less than maximum transferred copper rate and this value comes from copper solvent extraction circuit. The value of transferred copper is **11.3** t/h.

- In the excel cell “**F85**” (transferred copper rate), type number “**11.3**”.
- In the excel cell “**F86**” (copper production rate –t/h), type “ $=F64*F62*F44*F82*F63*10^{-6}$ ”.
- In the excel cell “**F87**” (copper production rate – t/y), type “ $=F86*F60$ ”.

## 2. Calculation of electrolyte flow parameters

### • Spent electrolyte flow

The known parameters of the spent electrolyte flow are:

- Spent electrolyte iron tenor
  - Spent electrolyte acid tenor
  - Spent electrolyte volume flowrate
- In the excel cell “**D10**” (spent electrolyte volume flowrate), type “ $=F65$ ”.
  - In the excel cell “**D15**” (spent electrolyte iron tenor), type “ $=F75$ ”.
  - In the excel cell “**D16**” (spent electrolyte acid tenor), type “ $=F74$ ”.

The operating current density is an unknown parameter and it becomes a solver variable. The starting value of the operating current density is the design current density (**300** A/m<sup>2</sup>).

- In the excel cell “**F44**” (operating current density), type number “**300**” (blue color).

The spent electrolyte copper tenor has different values when the operating value is greater or less than 350 A/m<sup>2</sup>.

- In the excel cell “**F88**” (spent electrolyte copper tenor), type “ $=if(F44<350,35,(F44/F59))$ ”.
- In the excel cell “**D14**” (spent electrolyte copper tenor), type “ $=F88$ ”.
- In the excel cell “**D13**” (spent electrolyte total salt tenor), type “ $=D14*F68+D15*F69+D16*F67$ ”.
- In the excel cell “**D11**” (spent electrolyte SG), type “ $=(-6.139*10^{-4}*D13^2+0.9742*D13+1000)/1000$ ”.
- In the excel cell “**D9**” (spent electrolyte mass flowrate), type “ $=D10*D11$ ”.
- In the excel cell “**D18**” (spent electrolyte copper mass flowrate), type “ $=D10*D14$ ”.
- In the excel cell “**D19**” (spent electrolyte iron mass flowrate), type “ $=D10*D15$ ”.
- In the excel cell “**D20**” (spent electrolyte acid mass flowrate), type “ $=D10*D16$ ”.

### • Iron bleed flow

The known parameters of the iron bleed flow are:

- Iron bleed copper tenor
  - Iron bleed iron tenor
  - Iron bleed acid tenor
- In the excel cell “**I34**” (iron bleed copper tenor), type “ $=D14$ ”.
  - In the excel cell “**I35**” (iron bleed iron tenor), type “ $=D15$ ”.
  - In the excel cell “**I36**” (iron bleed acid tenor), type “ $=D16$ ”.
  - In the excel cell “**I33**” (iron bleed total salt tenor), type “ $=I34*F68+I35*F69+I36*F67$ ”.

- In the excel cell “**I31**” (iron bleed liquid SG), type “ $=(-6.139*10^{-4}*I33^2+0.9742*I33+1000)/1000$ ”.

The ratio of iron bleed flowrate/spent electrolyte flowrate is an unknown value and it becomes a solver variable. The starting value of the ratio of iron bleed flowrate/spent electrolyte flowrate is “**1.00**”.

- In the excel cell “**F43**”, type number “**1.00**” (blue color).
- In the excel cell “**I30**” (iron bleed liquid volume flowrate), type “ $=D10*F43/100$ ”.
- In the excel cell “**I29**” (iron bleed liquid mass flowrate), type “ $=I30*I31$ ”.
- In the excel cell “**I38**” (iron bleed copper mass flowrate), type “ $=I30*I34$ ”.
- In the excel cell “**I39**” (iron bleed iron mass flowrate), type “ $=I30*I35$ ”.
- In the excel cell “**I40**” (iron bleed acid mass flowrate), type “ $=I30*I36$ ”.

- Advance electrolyte flow

- In the excel cell “**E18**” (advance electrolyte copper mass flowrate), type “ $=D18+I38+F86*1000$ ”.
- In the excel cell “**E19**” (advance electrolyte iron mass flowrate), type “ $=D19+(E18-D18)/F58$ ”.

Assuming that iron is transported into the copper electrowinning circuit by chemical transfer way; in consequence all transferred iron are iron III.

- In the excel cell “**E20**” (advance electrolyte acid mass flowrate), type “ $=D20+(D18-E18)*98/63.55+(D19-E19)*3*98/(2*55.85)$ ” where 98, 63.55 and 55.85 are the molar masses of acid, copper and iron.

The advance electrolyte volume flowrate is an unknown parameter and it becomes a solver variable. The starting value of the advance electrolyte volume flowrate is the value of the spent electrolyte volume flowrate.

- In the excel cell “**E10**” (advance electrolyte volume flowrate), type number “**567.71**”.
- In the excel cell “**E14**” (advance electrolyte copper tenor), type “ $=E18/E10$ ”.
- In the excel cell “**E15**” (advance electrolyte iron tenor), type “ $=E19/E10$ ”.
- In the excel cell “**E16**” (advance electrolyte acid tenor), type “ $=E20/E10$ ”.
- In the excel cell “**E13**” (advance electrolyte total salt tenor), type “ $=E14*F68+E15*F69+E16*F67$ ”.
- In the excel cell “**E11**” (advance electrolyte SG), type “ $=(-6.139*10^{-4}*E13^2+0.9742*E13+1000)/1000$ ”.
- In the excel cell “**E9**” (advance electrolyte liquid mass flowrate), type “ $=E10*E11$ ”.

- Solver set objective, constraint 1, and constraint 2

- In the excel cell “**D47**” (solver set objective), type “ $=(E18-D18)/(F85*1000)-1$ ”. The color of number into the excel cell “**D47**” is green.
- In the excel cell “**D48**” (constraint 1), type “ $=D9-(E18-D18)/1000+(E19-D19)/1000+(E20-D20)/1000*2/98-E9$ ” where 2 and 98 are the molar masses of 2 hydrogen atoms and acid. The color of number into the excel cell “**D48**” is green.
- In the excel cell “**D49**” (constraint 2), type “ $=(E19-D19)/I39-1$ ”.

- Copper cathode solid mass flowrate of scavenger circuit

- In the excel cell “**F6**” (copper cathode solid mass flowrate), type “ $=F64*F62*F44*F73*F71*F63*10^{-6}$ ”.

- Oxygen gas mass flowrate of scavenger circuit

- In the excel cell “**G7**” (oxygen gas mass flowrate), type “ $=F6*16/63.55$ ” where 16 and 63.55 are the atomic masses of oxygen and copper.

- Scavenger electrolyte flow

- In the excel cell “**H9**” (scavenger electrolyte liquid mass flowrate), type “=**E9-F6-G7**”.
- In the excel cell “**H18**” (scavenger electrolyte copper mass flowrate), type “=**E18-F6\*1000**”.
- In the excel cell “**H19**” (scavenger electrolyte iron mass flowrate), type “=**E19**”.
- In the excel cell “**H20**” (scavenger electrolyte acid mass flowrate), type “=**E20+(E18-H18)\*98/63.55**” where 98 and 63.55 are molar masses of acid and copper.

The scavenger electrolyte liquid volume flowrate is an unknown parameter and it is a solver variable. The starting value of scavenger electrolyte liquid volume flowrate is the value of advance electrolyte liquid volume flowrate.

- In the excel cell “**H10**”, type number “**567.71**” (blue color).
- In the excel cell “**H14**” (scavenger electrolyte copper tenor), type “=**H18/H10**”.
- In the excel cell “**H15**” (scavenger electrolyte iron tenor), type “=**H19/H10**”.
- In the excel cell “**H16**” (scavenger electrolyte acid tenor), type “=**H20/H10**”.
- In the excel cell “**H13**” (scavenger electrolyte total salt tenor), type “=**H14\*F68+H15\*F69+H16\*F67**”.
- In the excel cell “**H11**” (scavenger electrolyte SG), type “=**(-6.139\*10^-4\*H13^2+0.9742\*H13+1000)/1000**”.
- In the excel cell “**F89**” (electrolyte flowrate per cell into the scavenger), type “=**E10/F73**”.
- In the excel cell “**F90**” (cathode face velocity for scavenger cells), type “=**F89/(F71\*F62)**”.

- Solver constraint 3

- In the excel cell “**D50**” (solver constraint 3), type “=**H9-H10\*H11**”. The color of number into the excel cell “**D50**” is green.

- Feed commercial flow

- In the excel cell “**F91**” (electrolyte flowrate per cell into commercial), type “=**F71\*F62\*F66**”.
- In the excel cell “**F92**” (number of cells of commercial circuit), type “=**F72-F73**”.
- In the excel cell “**E30**” (feed commercial electrolyte liquid volume flowrate), type “=**F91\*F92**”.

The feed commercial electrolyte copper, iron, and acid tenors are unknown parameters. They become solver variables. The starting values of feed commercial electrolyte copper, iron, and acid tenors are respectively the values of scavenger electrolyte copper, iron, and acid tenors.

- In the excel cell “**E34**” (feed commercial electrolyte copper tenor), type number “**47.63**” (blue color).
- In the excel cell “**E35**” (feed commercial electrolyte iron tenor), type number “**1.03**” (blue color).
- In the excel cell “**E36**” (feed commercial electrolyte acid tenor), type number “**160.45**” (blue color).
- In the excel cell “**E33**” (feed commercial electrolyte total salt tenor), type “=**E34\*F68+E35\*F69+E36\*F67**”.
- In the excel cell “**E31**” (feed commercial electrolyte SG), type “=**(-6.139\*10^-4\*E33^2 +0.9742\*E33 +1000)/1000**”.
- In the excel cell “**E29**” (feed commercial electrolyte liquid mass flowrate), type “=**E30\*E31**”.
- In the excel cell “**E38**” (feed commercial electrolyte copper mass flowrate), type “=**E30\*E34**”.
- In the excel cell “**E39**” (feed commercial electrolyte iron mass flowrate), type “=**E30\*E35**”.
- In the excel cell “**E40**” (feed commercial electrolyte acid mass flowrate), type “=**E30\*E36**”.

- Copper cathode solid mass flowrate of commercial circuit

- In the excel cell “**F26**” (copper cathode solid mass flowrate), type “=**F86-F6**”.

- Oxygen gas mass flowrate of commercial circuit

- In the excel cell “G27” (oxygen gas mass flowrate), type “=F26\*16/63.55” where 16 and 63.55 are the atomic masses of oxygen and copper.

- Out commercial electrolyte

The known parameters of the out commercial electrolyte flow are:

- Out commercial electrolyte copper tenor
  - Out commercial electrolyte iron tenor
  - Out commercial electrolyte acid tenor
- In the excel cell “H34” (out commercial electrolyte copper tenor), type “=I34”.
  - In the excel cell “H35” (out commercial electrolyte iron tenor), type “=I35”.
  - In the excel cell “H36” (out commercial electrolyte acid tenor), type “=I36”.
  - In the excel cell “H33” (out commercial electrolyte total salt tenor), type “=H34\*F68+H35\*F69+H36\*F67”.
  - In the excel cell “H31” (out commercial electrolyte SG), type “=(-6.139\*10^-4\*H33^2 +0.9742\*H33 +1000)/1000”.
  - In the excel cell “H29” (out commercial electrolyte liquid mass flowrate), type “=E29-F26-G27”.
  - In the excel cell “H30” (out commercial electrolyte liquid volume flowrate), type “=H29/H31”.
  - In the excel cell “H38” (out commercial electrolyte copper mass flowrate), type “=E38-F26\*1000”.
  - In the excel cell “H39” (out commercial electrolyte iron mass flowrate), type “=E39”.
  - In the excel cell “H40” (feed commercial electrolyte acid mass flowrate), type “=E40+(E38-H38)\*98/63.55”.

Solver constraints 4, 5 and 6

- In the excel cell “D51” (solver constraint 3), type “=H38/H30-H34”. The color of number of “D51” is green.
- In the excel cell “G47” (solver constraint 4), type “=H39/H30-H35”. The color of number of “G47” is green.
- In the excel cell “G48” (solver constraint 5), type “=H40/H30-H36”. The color of number of “G48” is green.

- Recycle electrolyte

The known parameters of the recycle electrolyte flow are:

- Recycle electrolyte copper tenor
  - Recycle electrolyte iron tenor
  - Recycle electrolyte acid tenor
- In the excel cell “I14” (recycle electrolyte copper tenor), type “=I34”.
  - In the excel cell “I15” (recycle electrolyte iron tenor), type “=I35”.
  - In the excel cell “I16” (recycle electrolyte acid tenor), type “=I36”.
  - In the excel cell “I13” (recycle electrolyte total salt tenor), type “=I14\*F68+I15\*F69+I16\*F67”.
  - In the excel cell “I11” (recycle electrolyte SG), type “=(-6.139\*10^-4\*I13^2 +0.9742\*I13 +1000)/1000”.
  - In the excel cell “I9” (recycle electrolyte liquid mass flowrate), type “=H29-I29-D9”.
  - In the excel cell “I10” (recycle electrolyte liquid volume flowrate), type “=I9/I11”.
  - In the excel cell “I18” (recycle electrolyte copper mass flowrate), type “=I10\*I14”.
  - In the excel cell “I19” (recycle electrolyte iron mass flowrate), type “=I10\*I15”.
  - In the excel cell “I20” (recycle electrolyte acid mass flowrate), type “=I10\*I16”.

- Acid flow

The known parameter of the acid flow is:

- Acid SG

- In the excel cell “**D31**” (acid SG), type number “**1.84**”.
- In the excel cell “**D40**” (acid flow acid mass flowrate), type “=**E40-I20-H20**”.
- In the excel cell “**D29**” (acid flow liquid mass flowrate), type “=**(D40/0.98)/1000**” where 0.98 is mass fraction (w/w) of pure acid into the industrial acid.
- In the excel cell “**D30**” (acid flow liquid volume flowrate), type “=**D29/D31**”.

- Water flow

The known parameter of the water flow is:

- Water SG

- In the excel cell “**J11**” (water SG), type number “**1.000**”.
- In the excel cell “**J9**” (water liquid mass flowrate), type “=**E29-D29-I9-H9**”.
- In the excel cell “**J10**” (water liquid volume flowrate), type “=**J9/J11**”.

At this level, it appears Table 14 as it appears on Excel Microsoft spreadsheet. Table 14 gives simulation results of copper electrowinning circuit with the starting values of solver variables. Simulation results are not optimized. Excel solver program will be used for the optimization.

### 3. *Excel solver program*

Excel solver program execution is as follows:

- 1) On the ‘**Data**’, in the ‘**Analysis group**’ click **solver** (if the solver command is not available, you must activate the solver add-in).
- 2) In the ‘**Set objective**’ box, enter the cell reference ‘**D47**’ of simulation constraint table.
- 3) Click ‘**Value of**’ and then type the number ‘**0**’ in the box.
- 4) In the ‘**By Changing Variable Cells**’ box, enter the reference for each solver variable (blue color in Table 14 and simulation variable table). Separate the references with commas (English version).
- 5) In the ‘**Subject to the constraints**’ box, enter solver constraints by doing the following:
  - a. In the ‘**Solver Parameters**’ dialog box, click ‘**Add**’.
  - b. In the ‘**Cell Reference**’ box, enter the cell reference of constraint 1 (green color in Table 14).
  - c. Click the ‘**relationship**’ ‘**=**’, in the ‘**Constraint**’ box, type the number ‘**0**’.
  - d. Click ‘**Add**’ for the solver constraint 2. When the last solver constraint is added (cell ‘**G48**’), click ‘**OK**’ to return to ‘**Solver Parameters**’ dialog box.
- 6) Click ‘**Solve**’. To keep the solution values on the worksheet, in the ‘**Solver Results**’ dialog box, click ‘**Keep solver solution**’.

At this level, it appears Table 15 as it appears on Excel Microsoft spreadsheet. Table 15 gives optimized simulation results of copper electrowinning circuit.

### 4. *Calculation of other parameters*

- In the excel cell “**F93**” (harvest cycle), type “=**F79\*1000/(F64\*F62\*F44\*F63\*12)**”.
- In the excel cell “**F94**” (operating harvest cycle), type “=**ROUNDUP (F93,0)**”.
- In the excel cell “**F95**” (number of unloaded cathodes per day), type “=**F82/F94**”.

	A	B	C	D	E	F	G	H	I	J	K
1											
2		<b>Table</b>	<b>14A</b>	<b>Simulation table of copper electrowinning circuit</b>							
3											
4				1	2	3	4	5	6	7	
5		Designation		Sp El	Ad El	Sc CC	ScOx	ScEl	Re El	Water	
6		Solid mass	t/h			1.544					
7		Gas Mass	t/h				0.389				
8		Liquid									
9		Mass	t/h	691.9	697.2			695.3	2498.5	53.76	
10		Volume	m <sup>3</sup> /h	567.7	567.7			567.7	2050.2	53.76	
11		SG	t/m <sup>3</sup>	1.219	1.228			1.226	1.219	1.000	
12											
13		$C_t^s$	g/l	270.60	285.48			282.85	270.60		
14		Cu	g/l	35.00	50.35			47.63	35.00		
15		Fe	g/l	1.00	1.03			1.03	1.00		
16		Acid	g/l	180.00	156.25			160.45	180.00		
17											
18		Cu	Kg/h	19869.9	28586.7			27042.8	71756.7		
19		Fe	Kg/h	567.7	582.2			582.2	2050.2		
20		Acid	Kg/h	102187.8	88707.3			91088.2	369034.7		
21											
22		<b>Table</b>	<b>14B</b>	<b>Simulation table of copper electrowinning circuit</b>							
23											
24				8	9	10	11	12	13		
25		Designation		Acid	FCoEl	CoCC	CoOx	CoEl	FeBl		
26		Solid Mass	t/h			6.974					
27		Gas Mass	t/h				1.756				
28		Liquid									
29		Mass	t/h	-41.52	3206.0			3197.3	6.92		
30		Volume	m <sup>3</sup> /h	-22.57	2614.1			2623.6	5.68		
31		SG	t/m <sup>3</sup>	1.840	1.226			1.219	1.219		
32											
33		$C_t^s$	g/l		282.85			270.60	270.60		
34		Cu	g/l		47.63			35.00	35.00		
35		Fe	g/l		1.03			1.00	1.00		
36		Acid	g/l		160.46			180.00	180.00		
37											
38		Cu	Kg/h		124508.6			117534.3	198.7		
39		Fe	Kg/h		2692.5			2692.5	5.7		
40		Acid	Kg/h	-40693.9	419428.9			430183.9	1021.9		
41											
42		<b>Simulation additional solver variable table</b>									
43		Fe bleed flowrate/spent electrolyte flowrate				<b>1</b>	%				
44		Operating current density				<b>300</b>	A/m <sup>2</sup>				
45											
46		<b>Simulation solver constraint table</b>									
47		Set objective		<b>-0.229</b>	Constraint 5		<b>0.026</b>				
48		Constraint 1		<b>3.111</b>	Constraint 6		<b>-16.032</b>				
49		Constraint 2		<b>1.559</b>							
50		Constraint 3		<b>-0.997</b>							
51		Constraint 4		<b>9.799</b>							
52											

	A	B	C	D	E	F	G	H	I	J	K
53	<b>Simulation table data</b>										
54	Maximum current amperage of rectifier					<b>65.68</b>	KA				
55	Maximum current density of rectifier					<b>395</b>	A/m <sup>2</sup>				
56	Maximum operating current density					<b>375.25</b>	A/m <sup>2</sup>				
57	Spent electrolyte iron tenor					<b>1.00</b>	g/l				
58	Ratio of stripped Cu on stripped Fe					<b>600</b>					
59	Ratio of OCD on spent electrolyte copper tenor					<b>9.7</b>					
60	Working hours per year					<b>8322</b>	hrs				
61	Type of cathode blank					<b>ISA</b>					
62	Cathode active area					<b>2.41</b>	m <sup>2</sup>				
63	Current efficiency					<b>0.9</b>					
64	Constant K					<b>1.1858</b>	g/A-hrs				
65	Design spent electrolyte flowrate					<b>567.71</b>	m <sup>3</sup> /h				
66	Cathode face velocity					<b>0.12</b>	m <sup>3</sup> /h/m <sup>2</sup>				
67	Constant $\alpha_1$ (acid)					<b>1.000</b>					
68	Constant $\alpha_2$ (copper)					<b>2.511</b>					
69	Constant $\alpha_4$ (iron)					<b>2.719</b>					
70	Spent electrolyte acid tenor					<b>180</b>	g/l				
71	Number of cathodes per cell					<b>69</b>					
72	Number of cells per cell house					<b>160</b>					
73	Number of cells/scavenger circuit					<b>29</b>					
74	Number of cranes					<b>2</b>					
75	Number of rectifiers					<b>2</b>					
76	Number of stripping machines					<b>2</b>					
77	Stripping method					<b>manual</b>					
78	Stripping machine working hours/day					<b>19</b>	hrs				
79	Weight of one side copper deposit					<b>60</b>	kg				
80											
81	<b>Simulation table results</b>										
82	Number of cathodes/cell house					11040					
83	Maximum production rate					10.65	t/h				
84	Maximum transferred copper rate					11.39	t/h				
85	Transferred copper rate					11.30	t/h				
86	Production rate					8.52	t/h				
87	Production rate					70888.27	h/y				
88	Spent electrolyte copper tenor					35.00	g/l				
89	Electrolyte flowrate per cell/scavenger					19.58	m <sup>3</sup> /h				
90	Cathode face velocity/scavenger					0.118	(m <sup>3</sup> /h)/m <sup>2</sup>				
91	Electrolyte flowrate per cell/commercial					19.95	m <sup>3</sup> /h				
92	Number of cells/commercial					131					
93	Harvest cycle						days				
94	Operating harvest cycle						days				
95	Number of unloaded cathodes/day										
96	Number of unloaded cathodes/crane										
97	Number of crane revolutions/day										
98	Number of crane revolution/day/crane										
99	Number of cells/rectifier										
100	Cell voltage						V				
101	Total cell voltage per rectifier						V				
102	Bus-bar and losses voltage						V				
103	Total rectifier voltage						V				
104	Operating current amperage						kA				
105	Operating rectifier power						kW				
106	Capacity of stripping machine						Cathodes/h				
107											

	A	B	C	D	E	F	G	H	I	J	K	
1												
2		<b>Table</b>	<b>15A</b>	<b>Simulation table of copper electrowinning circuit</b>								
3												
4				1	2	3	4	5	6	7		
5		Designation		Sp El	Ad El	Sc CC	ScOx	ScEl	Re El	Water		
6		Solid mass	t/h			1.917						
7		Gas Mass	t/h				0.483					
8		Liquid										
9		Mass	t/h	694.9	705.9			703.5	2474.4	20.68		
10		Volume	m <sup>3</sup> /h	567.7	571.7			570.5	2022.2	20.68		
11		SG	t/m <sup>3</sup>	1.224	1.235			1.233	1.224	1.000		
12												
13		$C_t^s$	g/l	279.15	296.37			293.73	279.15			
14		Cu	g/l	38.40	57.90			54.66	38.40			
15		Fe	g/l	1.00	1.03			1.03	1.00			
16		Acid	g/l	180.00	148.18			153.68	180.00			
17												
18		Cu	Kg/h	21801.3	33101.3			31184.2	77658.2			
19		Fe	Kg/h	567.7	586.5			586.5	2022.2			
20		Acid	Kg/h	102187.8	84712.6			87668.8	364002.5			
21												
22		<b>Table</b>	<b>15B</b>	<b>Simulation table of copper electrowinning circuit</b>								
23												
24				8	9	10	11	12	13			
25		Designation		Acid	FCoEl	CoCC	CoOx	CoEl	FeBl			
26		Solid Mass	t/h			8.660						
27		Gas Mass	t/h				2.180					
28		Liquid										
29		Mass	t/h	4.65	3204.3			3193.4	23.05			
30		Volume	m <sup>3</sup> /h	2.53	2614.1			2608.8	18.83			
31		SG	t/m <sup>3</sup>	1.840	1.226			1.224	1.224			
32												
33		$C_t^s$	g/l		281.79			279.15	279.15			
34		Cu	g/l		41.64			38.40	38.40			
35		Fe	g/l		1.00			1.00	1.00			
36		Acid	g/l		174.53			180.00	180.00			
37												
38		Cu	Kg/h		108842.4			100182.7	723.24			
39		Fe	Kg/h		2608.8			2608.8	18.83			
40		Acid	Kg/h	4554.9	456226.2			469580.5	3390.00			
41												
42		<b>Simulation additional solver variable table</b>										
43		Fe bleed flowrate/spent electrolyte flowrate				3.32		%				
44		Operating current density				372.50		A/m <sup>2</sup>				
45												
46		<b>Simulation solver constraint table</b>										
47		Set objective		0.000	Constraint 5		0.000					
48		Constraint 1		0.000	Constraint 6		0.000					
49		Constraint 2		0.000								
50		Constraint 3		0.000								
51		Constraint 4		0.000								
52												

	A	B	C	D	E	F	G	H	I	J	K	
53	<b>Simulation table data</b>											
54		Maximum current amperage of rectifier				<b>65.68</b>	KA					
55		Maximum current density of rectifier				<b>395</b>	A/m <sup>2</sup>					
56		Maximum operating current density				<b>375.25</b>	A/m <sup>2</sup>					
57		Spent electrolyte iron tenor				<b>1.00</b>	g/l					
58		Ratio of stripped Cu on stripped Fe				<b>600</b>						
59		Ratio of OCD on spent electrolyte copper tenor				<b>9.7</b>						
60		Working hours per year				<b>8322</b>	hrs					
61		Type of cathode blank				<b>ISA</b>						
62		Cathode active area				<b>2.41</b>	m <sup>2</sup>					
63		Current efficiency				<b>0.9</b>						
64		Constant K				<b>1.1858</b>	g/A-hrs					
65		Design spent electrolyte flowrate				<b>567.71</b>	m <sup>3</sup> /h					
66		Cathode face velocity				<b>0.12</b>	m <sup>3</sup> /h/m <sup>2</sup>					
67		Constant $\alpha_1$ (acid)				<b>1.000</b>						
68		Constant $\alpha_2$ (copper)				<b>2.511</b>						
69		Constant $\alpha_4$ (iron)				<b>2.719</b>						
70		Spent electrolyte acid tenor				<b>180</b>	g/l					
71		Number of cathodes per cell				<b>69</b>						
72		Number of cells per cell house				<b>160</b>						
73		Number of cells/scavenger circuit				<b>29</b>						
74		Number of cranes				<b>2</b>						
75		Number of rectifiers				<b>2</b>						
76		Number of stripping machines				<b>2</b>						
77		Stripping method				<b>manual</b>						
78		Stripping machine working hours/day				<b>19</b>	hrs					
79		Weight of one side copper deposit				<b>60</b>	kg					
80												
81	<b>Simulation table results</b>											
82		Number of cathodes/cell house				11040						
83		Maximum production rate				10.65	t/h					
84		Maximum transferred copper rate				11.39	t/h					
85		Transferred copper rate				11.30	t/h					
86		Production rate				10.58	t/h					
87		Production rate				88019.79	h/y					
88		Spent electrolyte copper tenor				38.40	g/l					
89		Electrolyte flowrate per cell/scavenger				19.71	m <sup>3</sup> /h					
90		Cathode face velocity/scavenger				0.119	(m <sup>3</sup> /h)/m <sup>2</sup>					
91		Electrolyte flowrate per cell/commercial				19.95	m <sup>3</sup> /h					
92		Number of cells/commercial				131						
93		Harvest cycle				5.22	days					
94		Operating harvest cycle				6	days					
95		Number of unloaded cathodes/day				1840						
96		Number of unloaded cathodes/crane				23						
97		Number of crane revolutions/day				80						
98		Number of crane revolution/day/crane				40						
99		Number of cells/rectifier				80						
100		Cell voltage				2.18	V					
101		Total cell voltage per rectifier				174.72	V					
102		Bus-bar and losses voltage				26.21	V					
103		Total rectifier voltage				200.93	V					
104		Operating current amperage				61.94	kA					
105		Operating rectifier power				12446.47	kW					
106		Capacity of stripping machine				48.42	Cathodes/h					
107												

- In the excel cell “F96” (number of unloaded cathodes per crane), type “=F71/3”.
- In the excel cell “F97” (number of crane revolutions per day), type “=F95/F96”.
- In the excel cell “F98” (number of crane revolutions/day/crane), type “=F97/F74”.
- In the excel cell “F99” (number of cells per rectifier), type “=F72/F75”.
- In the excel cell “F100” (cell voltage), type “=(1.57+7.69\*10<sup>-4</sup>\*F44)/0.85”.
- In the excel cell “F101” (total cell voltage per rectifier), type “=F100\*F99”.
- In the excel cell “F102” (Bus-bar and losses voltage), type “=F101\*15/100”.
- In the excel cell “F103” (total voltage per rectifier), type “=F101+F102”.
- In the excel cell “F104” (operating current amperage), type “=F71\*F62\*F44/1000”.
- In the excel cell “F105” (operating rectifier power), type “=F103\*F104”.
- In the excel cell “F106” (capacity of stripping machine), type “=(F82/F76)/(F94\*F78)”.

If the advance electrolyte copper tenor is greater than 55 g/l, to avoid the copper crystallization, the flowrate of the spent electrolyte flowrate must be increased. The mathematical expression (47) gives the new value of the spent electrolyte flowrate.

$$\text{Spent electrolyte flowrate} = \frac{\text{Transferred copper rate} \times 1000}{(55 - \text{spent electrolyte copper tenor})} \quad (47)$$

*Where transferred copper rate and spent electrolyte copper tenor are expressed respectively in “t/h” and “g/l”.*

- In the excel cell “D10” (spent electrolyte flowrate), type “=F85\*1000/(55-F88)”.
- Click ‘Solve’. To keep the solution values on the worksheet, in the ‘Solver Results’ dialog box, click ‘Keep solver solution’.

At this level, it appears Table 16 as it appears on Excel Microsoft spreadsheet. Table 156 gives optimized simulation results of copper electrowinning circuit with the value of advance electrolyte copper tenor less than 55 g/l.

	A	B	C	D	E	F	G	H	I	J	K
1											
2		<b>Table</b>	<b>16A</b>	<b>Simulation table of copper electrowinning circuit</b>							
3											
4				1	2	3	4	5	6	7	
5		Designation		Sp El	Ad El	Sc CC	ScOx	ScEl	Re El	Water	
6		Solid mass	t/h			1.917					
7		Gas Mass	t/h				0.483				
8		Liquid									
9		Mass	t/h	833.4	844.3			841.9	2337.0	20.68	
10		Volume	m <sup>3</sup> /h	680.8	684.8			683.6	1909.1	20.68	
11		SG	t/m <sup>3</sup>	1.224	1.233			1.232	1.224	1.000	
12											
13		$C_t^s$	g/l	279.15	293.53			291.33	279.15		
14		Cu	g/l	38.40	54.68			51.97	38.40		
15		Fe	g/l	1.00	1.02			1.02	1.00		
16		Acid	g/l	180.00	153.44			158.04	180.00		
17											
18		Cu	Kg/h	26144.6	37444.6			35527.6	73314.9		
19		Fe	Kg/h	680.8	699.6			699.6	1909.1		
20		Acid	Kg/h	122546.0	105070.7			108027.0	343644.3		
21											
22		<b>Table</b>	<b>16B</b>	<b>Simulation table of copper electrowinning circuit</b>							
23											
24				8	9	10	11	12	13		
25		Designation		Acid	FCoEl	CoCC	CoOx	CoEl	FeBl		
26		Solid Mass	t/h			8.660					
27		Gas Mass	t/h				2.180				
28		Liquid									
29		Mass	t/h	4.65	3204.3			3193.4	23.05		
30		Volume	m <sup>3</sup> /h	2.53	2614.1			2608.8	18.83		
31		SG	t/m <sup>3</sup>	1.840	1.226			1.224	1.224		
32											
33		$C_t^s$	g/l		281.79			279.15	279.15		
34		Cu	g/l		41.64			38.40	38.40		
35		Fe	g/l		1.00			1.00	1.00		
36		Acid	g/l		174.53			180.00	180.00		
37											
38		Cu	Kg/h		108842.4			100182.7	723.24		
39		Fe	Kg/h		2608.8			2608.8	18.88		
40		Acid	Kg/h	4554.9	456226.2			469580.3	3390.0		
41											
42		<b>Simulation additional solver variable table</b>									
43		Fe bleed flowrate/spent electrolyte flowrate				2.77	%				
44		Operating current density				372.5	A/m <sup>2</sup>				
45											
46		<b>Simulation solver constraint table</b>									
47		Set objective		0.000	Constraint 5		0.000				
48		Constraint 1		0.000	Constraint 6		0.000				
49		Constraint 2		0.000							
50		Constraint 3		0.000							
51		Constraint 4		0.000							
52											

	A	B	C	D	E	F	G	H	I	J	K	
53	<b>Simulation table data</b>											
54		Maximum current amperage of rectifier				<b>65.68</b>	KA					
55		Maximum current density of rectifier				<b>395</b>	A/m <sup>2</sup>					
56		Maximum operating current density				<b>375.25</b>	A/m <sup>2</sup>					
57		Spent electrolyte iron tenor				<b>1.00</b>	g/l					
58		Ratio of stripped Cu on stripped Fe				<b>600</b>						
59		Ratio of OCD on spent electrolyte copper tenor				<b>9.7</b>						
60		Working hours per year				<b>8322</b>	hrs					
61		Type of cathode blank				<b>ISA</b>						
62		Cathode active area				<b>2.41</b>	m <sup>2</sup>					
63		Current efficiency				<b>0.9</b>						
64		Constant K				<b>1.1858</b>	g/A-hrs					
65		Design spent electrolyte flowrate				<b>567.71</b>	m <sup>3</sup> /h					
66		Cathode face velocity				<b>0.12</b>	m <sup>3</sup> /h/m <sup>2</sup>					
67		Constant $\alpha_1$ (acid)				<b>1.000</b>						
68		Constant $\alpha_2$ (copper)				<b>2.511</b>						
69		Constant $\alpha_4$ (iron)				<b>2.719</b>						
70		Spent electrolyte acid tenor				<b>180</b>	g/l					
71		Number of cathodes per cell				<b>69</b>						
72		Number of cells per cell house				<b>160</b>						
73		Number of cells/scavenger circuit				<b>29</b>						
74		Number of cranes				<b>2</b>						
75		Number of rectifiers				<b>2</b>						
76		Number of stripping machines				<b>2</b>						
77		Stripping method				<b>manual</b>						
78		Stripping machine working hours/day				<b>19</b>	hrs					
79		Weight of one side copper deposit				<b>60</b>	kg					
80												
81	<b>Simulation table results</b>											
82		Number of cathodes/cell house				11040						
83		Maximum production rate				10.65	t/h					
84		Maximum transferred copper rate				11.39	t/h					
85		Transferred copper rate				11.30	t/h					
86		Production rate				10.58	t/h					
87		Production rate				88019.79	h/y					
88		Spent electrolyte copper tenor				38.40	g/l					
89		Electrolyte flowrate per cell/scavenger				23.61	m <sup>3</sup> /h					
90		Cathode face velocity/scavenger				0.142	(m <sup>3</sup> /h)/m <sup>2</sup>					
91		Electrolyte flowrate per cell/commercial				19.95	m <sup>3</sup> /h					
92		Number of cells/commercial				131						
93		Harvest cycle				5.22	days					
94		Operating harvest cycle				6	days					
95		Number of unloaded cathodes/day				1840						
96		Number of unloaded cathodes/crane				23						
97		Number of crane revolutions/day				80						
98		Number of crane revolution/day/crane				40						
99		Number of cells/rectifier				80						
100		Cell voltage				2.18	V					
101		Total cell voltage per rectifier				174.72	V					
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103		Total rectifier voltage				200.93	V					
104		Operating current amperage				61.94	kA					
105		Operating rectifier power				12446.47	kW					
106		Capacity of stripping machine				48.42	Cathodes/h					
107												

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