# AN EVALUATION OF SOME POSSIBLE INTEGRATED FLOWSHEETS FOR THE PYROMETALLURGICAL RECOVERY OF COBALT, USING DC-ARC FURNACE TECHNOLOGY

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## ABSTRACT

The effective pyrometallurgical recovery of cobalt (and nickel, and copper) from non-ferrous smelter slags has been demonstrated using a DC-arc furnace. This process can be applied to either furnace or converter slag (or existing slag dumps). For the case of a base-metals smelter comprising a primary furnace and a converter (with an existing recycle of converter slag), a number of possible flowsheets have been evaluated in terms of overall cobalt recovery, power requirement, and capacity. The process options under consideration include the reduction of furnace and converter slag to form an alloy, as well as an upgrading (blowing) stage where the iron content of the alloy is decreased. A comparison has also been made between the use of an existing converter and the use of a separate additional converter.

Keywords: cobalt, copper, DC-arc, furnace, nickel, plasma, plasma-arc, pyrometallurgy, Pyrosim, recovery, reduction, slag, slag cleaning

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## INTRODUCTION

The effective pyrometallurgical recovery of cobalt (and nickel, and copper) from non-ferrous smelter slags has been demonstrated using a DC-arc furnace[1, 2]. This process can be applied to either furnace or converter slag (or existing slag dumps). For the case of a base-metals smelter comprising a primary furnace and a Peirce-Smith converter (with an existing recycle of converter slag), a number of possible flowsheets have been evaluated in terms of overall cobalt recovery, power requirement, and capacity.

The two primary options involve treating the primary furnace slag or the converter slag. Each of these two feed materials can be treated directly in a DC-arc furnace only, or in a DC-arc furnace followed by an upgrading (blowing) step. The resulting slag from the DC-arc furnace treatment of converter slag, may optionally be recycled to the primary smelting furnace. Alternatively, the upgrading step can be done in the existing Peirce-Smith converter.

## SIMULATION

The steady-state mass and energy balances for the different options were simulated using Mintek's Pyrosim computer software package[3]. For the simulations, chemical equilibrium between the gas, slag, and matte/alloy was assumed. Free-energy minimization, together with the Ideal Mixing of Complex Components solution modelling technique, was used to calculate the equilibrium composition of the different phases. The theoretical energy requirements (without any losses, in kWh per ton of concentrate fed) were calculated for each of the units for each flowsheet considered.

### Operating conditions

For the primary furnace it was assumed that 1.5 % of the matte produced was entrained in the slag. For the converters, matte entrainment of 5 % was assumed, while the entrainment for the slag-cleaning furnace (DC-arc furnace) was taken to be negligible.

The operating temperature of the primary furnace was taken at 1350 °C. An operating temperature of 1250 °C was used for the converter, 1550 °C for the DC-arc furnace, and 1400 °C for the additional converter (a top-blown rotary converter, TBRC, for example).

The operating pressure was taken to be 1 atm. for all the process units.

In both converters, adding silica and blowing with air was used to remove the iron from the matte (or alloy) and to produce a fayalite slag. Silica was added to obtain a $FeO:SiO_2$ ratio of 2.39, which corresponds to stoichiometric fayalite ($2FeO \cdot SiO_2$). Air was used to blow the iron down to 3 % (by mass) in the matte, in the first converter. In the TBRC, air was added to obtain an alloy containing 30 % (by mass) iron.

Limestone was added to the primary furnace to modify the slag composition so that the liquidus temperature was close to the operating temperature of the furnace. This resulted in a

$(CaO+MgO):SiO_2$ ratio of 0.41 by mass.

Coal was used as the reductant in the DC-arc furnace. The coal addition was adjusted so as to obtain a cobalt distribution of 80:20 between the alloy and the slag. (In practice slightly more coal may need to be added, because of burn-off in the DC-arc furnace.)

The following assumptions were made regarding the temperatures of interconnecting streams, when entering the next unit. The matte produced in the primary furnace is transferred to the converter at 1300 °C, the slag produced is transferred at 1200 °C. The converter slag entered the next unit ( the primary furnace or the DC-arc furnace) at 1100 °C. The alloy produced in the DC-arc furnace was transferred to the TBRC or existing converter at 1350 °C, while the slag was transferred at 1400 °C to the primary furnace. The slag produced in the TBRC was recycled to the DC-arc furnace at 1300 °C. These assumed temperatures affect primarily the energy requirements of the various process units, and have a lesser effect on the chemistry of the units.

## Feed materials

A concentrate feedrate of 1 000 kg/h was used as a base for the simulations. The composition of the hypothetical sulphide concentrate used in the simulations is given in Table 1.

**Table 1 Composition of hypothetical sulphide concentrate, mass %**

| $Al_2O_3$ | CaO | Co | $Cr_2O_3$ | Cu | Fe | MgO | Ni | S | $SiO_2$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| - | 3.2 | 0.3 | 0.5 | 4.0 | 32.0 | 10.0 | 8.0 | 21 | 21 | 100 |

The compositions of the additional feed materials (limestone, silica, and coal) are given in Table 2.

**Table 2 Compositions of other feed materials, mass %**

| | $Al_2O_3$ | C | $CaCO_3$ | CaO | $Fe_2O_3$ | FeO | $H_2O$ | MgO | S | $SiO_2$ | Volatiles | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Limestone** | 0.02 | - | 82.2 | 2.1 | - | 1.8 | - | 0.07 | - | 13.2 | - | 99.4 |
| **Coal** | 3.2 | 62.3 | - | 0.75 | 1.8 | - | 0.8 | 0.03 | 2.3 | 5.1 | 24 | 100.3 |
| **Silica** | 4.0 | - | - | 0.2 | - | 5.6 | - | 0.2 | - | 90.0 | - | 100.0 |

# FLOWSHEETS INVESTIGATED

## Base case

For the base case, a conventional base-metal smelter flowsheet was used. The concentrate is fed to a six-in-line furnace. The matte produced in the furnace is fed into a Peirce-Smith converter and the furnace slag is dumped. Air and flux (silica) are added to the matte in the converter to produce a 'white matte' that can be treated hydrometallurgically, and the converter slag is recycled back to the furnace. Figure 1 shows a schematic diagram for the base case investigated.

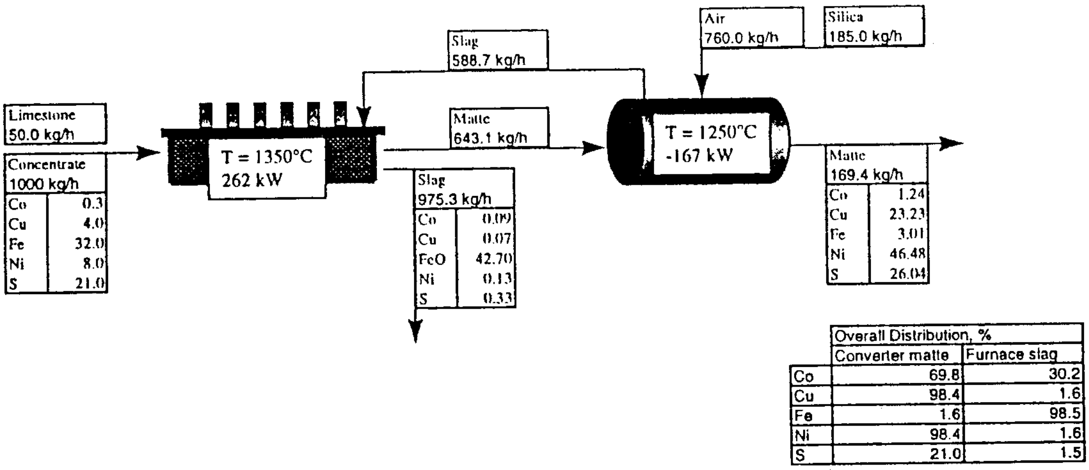



**Figure 1 Flowsheet of base case studied**

## Option 1 Furnace slag in DC-arc furnace

A DC-arc slag-cleaning furnace treats the liquid slag from the primary furnace. The alloy produced in the slag-cleaning furnace is treated hydrometallurgically, while the slag from the slag-cleaning furnace is discarded. The flowsheet for Option 1 is shown in Figure 2.

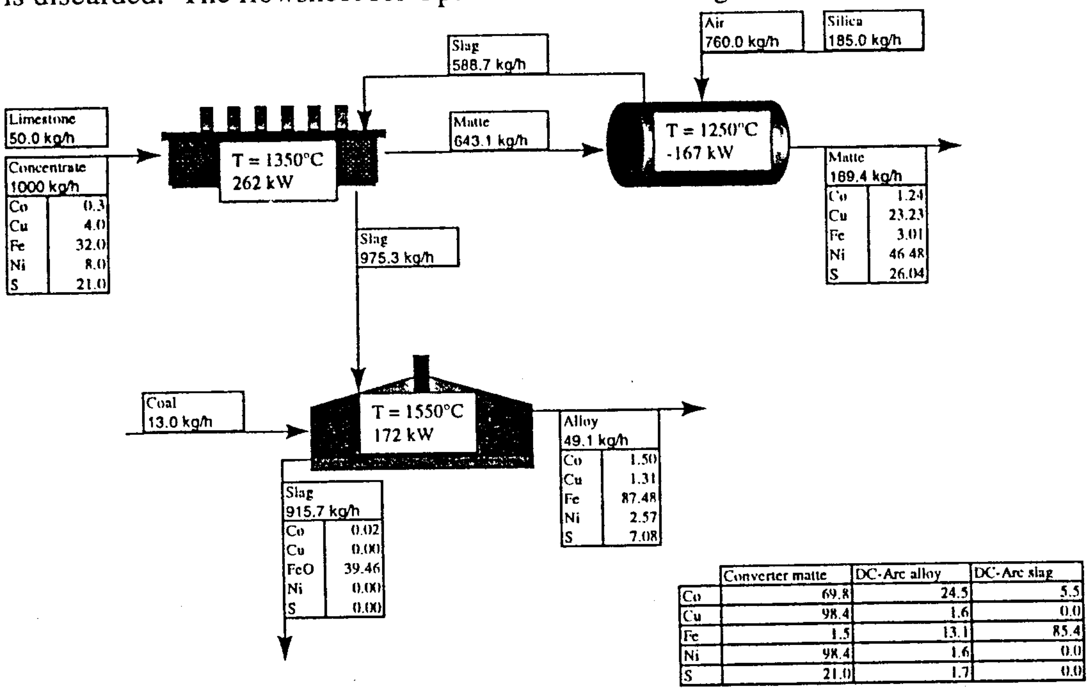
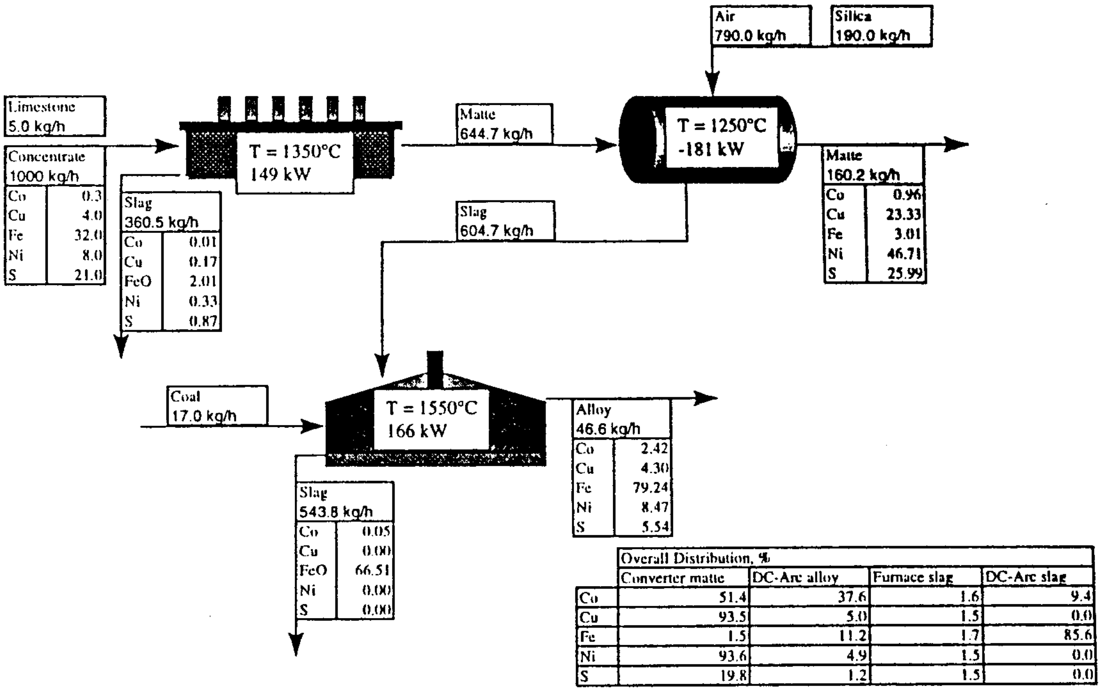



**Figure 2 Flowsheet for Option 1**

## Option 2 Converter slag in DC-arc furnace

A DC-arc slag-cleaning furnace treats the liquid converter slag. The alloy produced in the slag-cleaning furnace is treated hydrometallurgically, while the slag from the slag-cleaning furnace is discarded. The slag from the primary furnace is dumped. Figure 3 contains the flowsheet for this option.

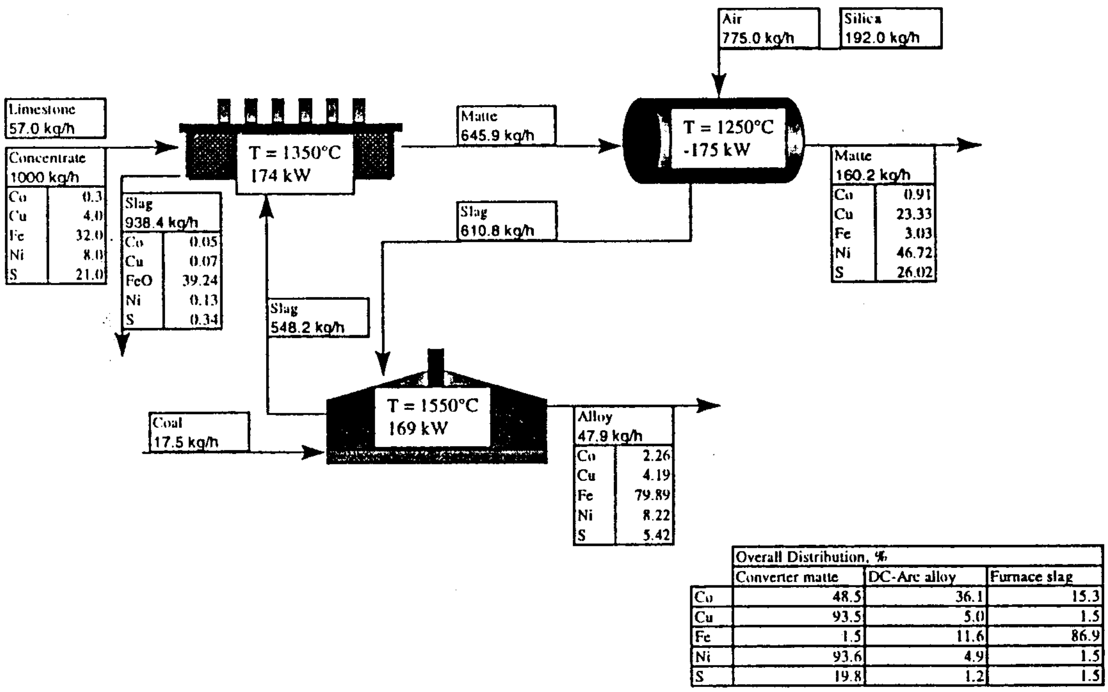



| Overall Distribution, % | Converter matte | DC-Arc alloy | Furnace slag | DC-Arc slag |
|---|---|---|---|---|
| Co | 51.4 | 37.6 | 1.6 | 9.4 |
| Cu | 93.5 | 5.0 | 1.5 | 0.0 |
| Fe | 1.5 | 11.2 | 1.7 | 85.6 |
| Ni | 93.6 | 4.9 | 1.5 | 0.0 |
| S | 19.8 | 1.2 | 1.5 | 0.0 |

**Figure 3 Flowsheet for Option 2**

## Option 3 Converter slag in DC-arc furnace, with recycle

A DC-arc slag-cleaning furnace treats the liquid converter slag. The alloy produced in the slag-cleaning furnace is treated hydrometallurgically, while the slag from the slag-cleaning furnace is recycled back to the primary furnace. The slag from the primary furnace is dumped. Figure 4 shows this flowsheet.

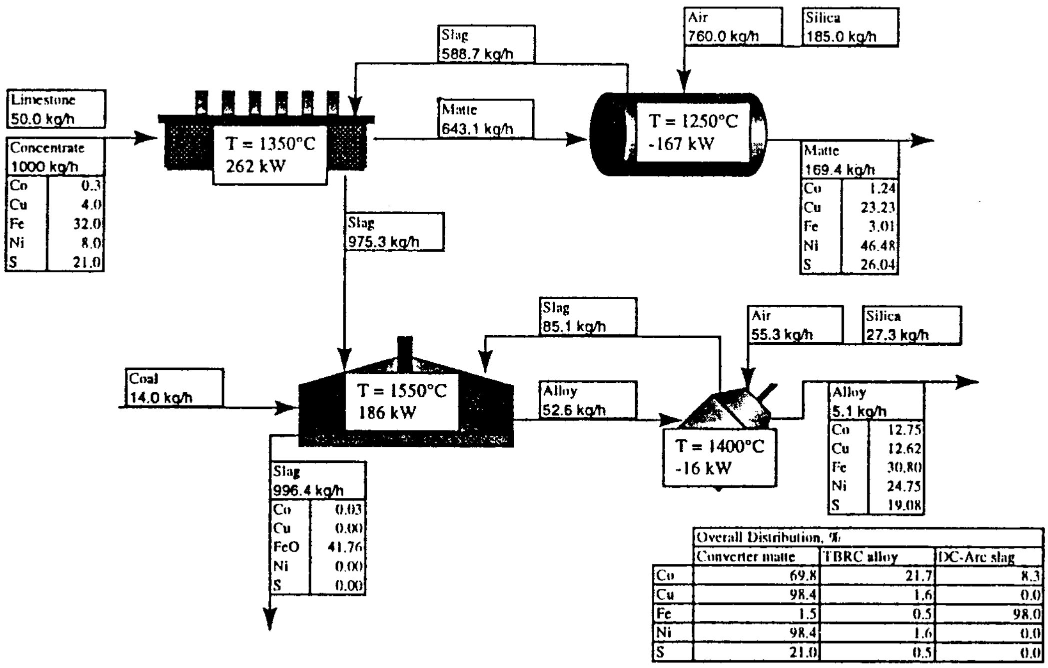



| Overall Distribution, % | Converter matte | DC-Arc alloy | Furnace slag |
|---|---|---|---|
| Co | 48.5 | 36.1 | 15.3 |
| Cu | 93.5 | 5.0 | 1.5 |
| Fe | 1.5 | 11.6 | 86.9 |
| Ni | 93.6 | 4.9 | 1.5 |
| S | 19.8 | 1.2 | 1.5 |

**Figure 4 Flowsheet for Option 3**

## Option 4 Furnace slag in DC-arc furnace and TBRC

A DC-arc slag-cleaning furnace treats the liquid slag from the primary furnace. The alloy produced in the slag-cleaning furnace is treated in a converter, the slag from this unit is recycled back to the slag-cleaning furnace. The slag from the slag-cleaning furnace is discarded. The flowsheet for Option 4 is shown in Figure 5.

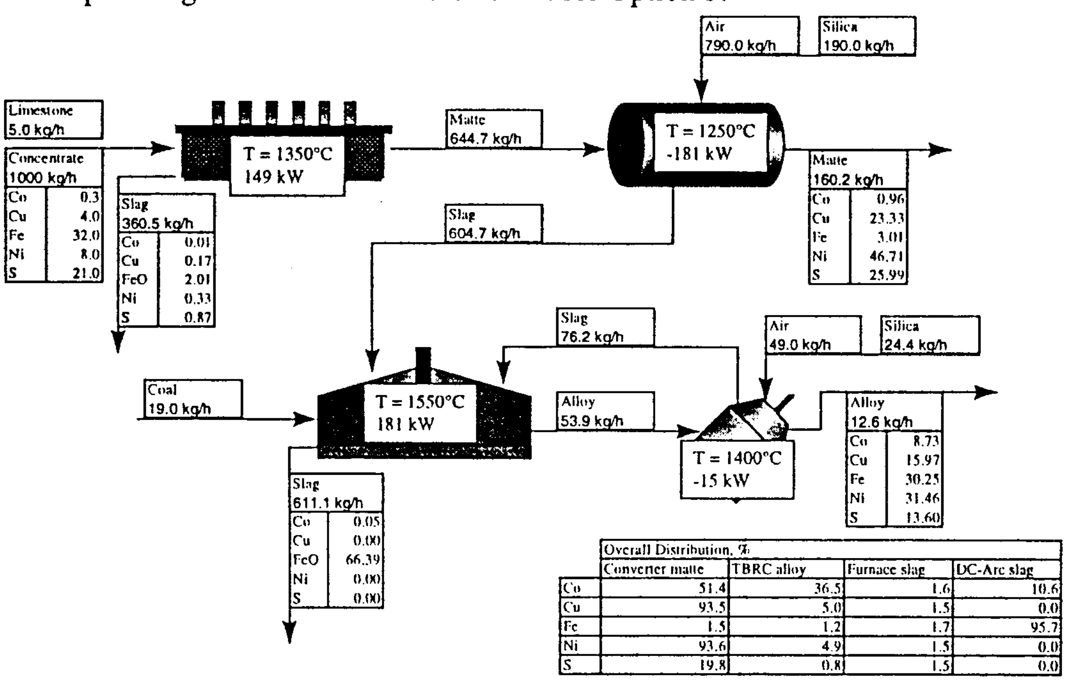



| | Overall Distribution, % | | |
|---|---|---|---|
| | Converter matte | TBRC alloy | DC-Arc slag |
| Co | 69.8 | 21.7 | 8.3 |
| Cu | 98.4 | 1.6 | 0.0 |
| Fe | 1.5 | 0.5 | 98.0 |
| Ni | 98.4 | 1.6 | 0.0 |
| S | 21.0 | 0.5 | 0.0 |

**Figure 5 Flowsheet for Option 4**

## Option 5 Converter slag in DC-arc furnace and TBRC

A DC-arc slag-cleaning furnace treats the liquid converter slag. The alloy produced in the slag-cleaning furnace is treated in a converter, the slag from this unit is recycled back to the slag-cleaning furnace. The slag from the slag-cleaning furnace is discarded. The slag from the primary furnace is dumped. Figure 6 contains the flowsheet for Option 5.

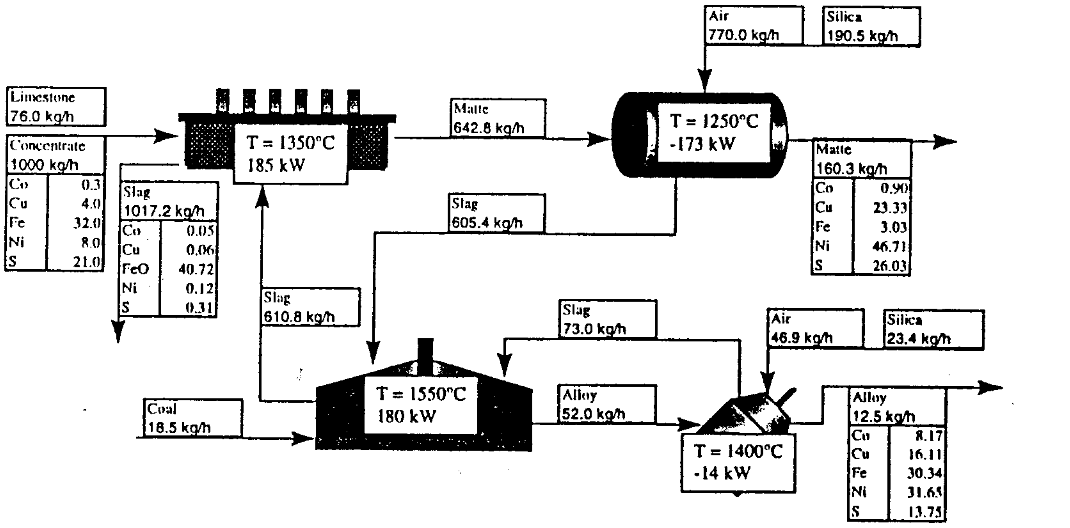



| | Overall Distribution, % | | | |
|---|---|---|---|---|
| | Converter matte | TBRC alloy | Furnace slag | DC-Arc slag |
| Co | 51.4 | 36.5 | 1.6 | 10.6 |
| Cu | 93.5 | 5.0 | 1.5 | 0.0 |
| Fe | 1.5 | 1.2 | 1.7 | 95.7 |
| Ni | 93.6 | 4.9 | 1.5 | 0.0 |
| S | 19.8 | 0.8 | 1.5 | 0.0 |

**Figure 6 Flowsheet for Option 5**

## Option 6 Converter slag in DC-arc furnace and TBRC, with recycle

A DC-arc slag-cleaning furnace treats the liquid converter slag. The alloy produced in the slag-cleaning furnace is treated in a converter, the slag from this unit is recycled back to the slag-cleaning furnace. The slag from the slag-cleaning furnace is recycled back to the primary furnace. The slag from the primary furnace is dumped. The flowsheet for Option 6 is shown in Figure 7.

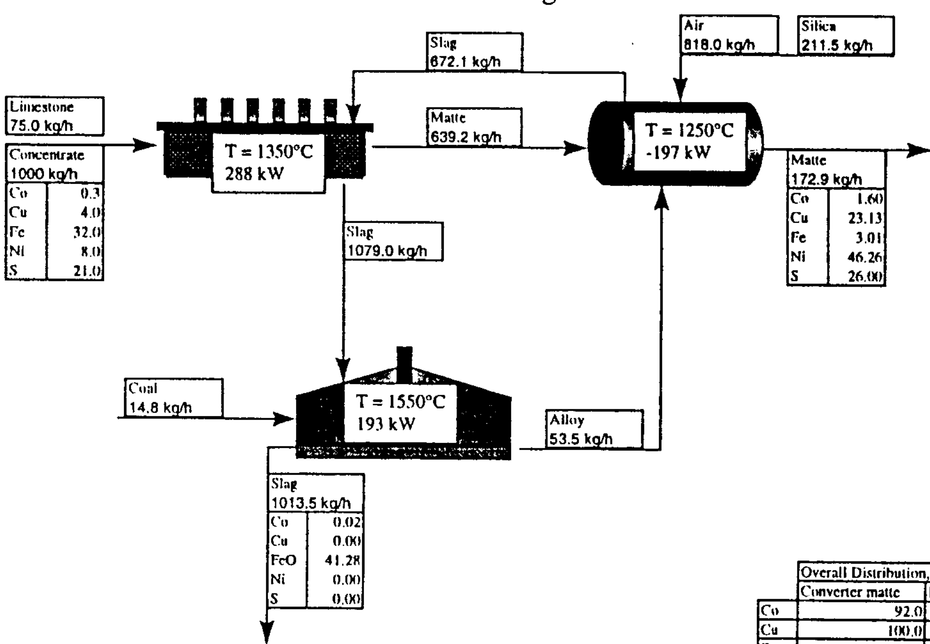



| | Overall Distribution, % | | |
|---|---|---|---|
| | Converter matte | TBRC alloy | Furnace slag |
| Co | 48.3 | 33.9 | 18.0 |
| Cu | 93.5 | 5.0 | 1.5 |
| Fe | 1.5 | 1.1 | 97.4 |
| Ni | 93.6 | 4.9 | 1.5 |
| S | 19.8 | 0.8 | 1.5 |

**Figure 7 Flowsheet for Option 6**

## Option 7 Furnace slag in DC-arc furnace and Peirce-Smith converter

A DC-arc slag-cleaning furnace treats the liquid slag from the primary furnace. The alloy produced in the slag-cleaning furnace is treated in an existing converter, while the slag from the slag-cleaning furnace is discarded. This flowsheet is shown in Figure 8.

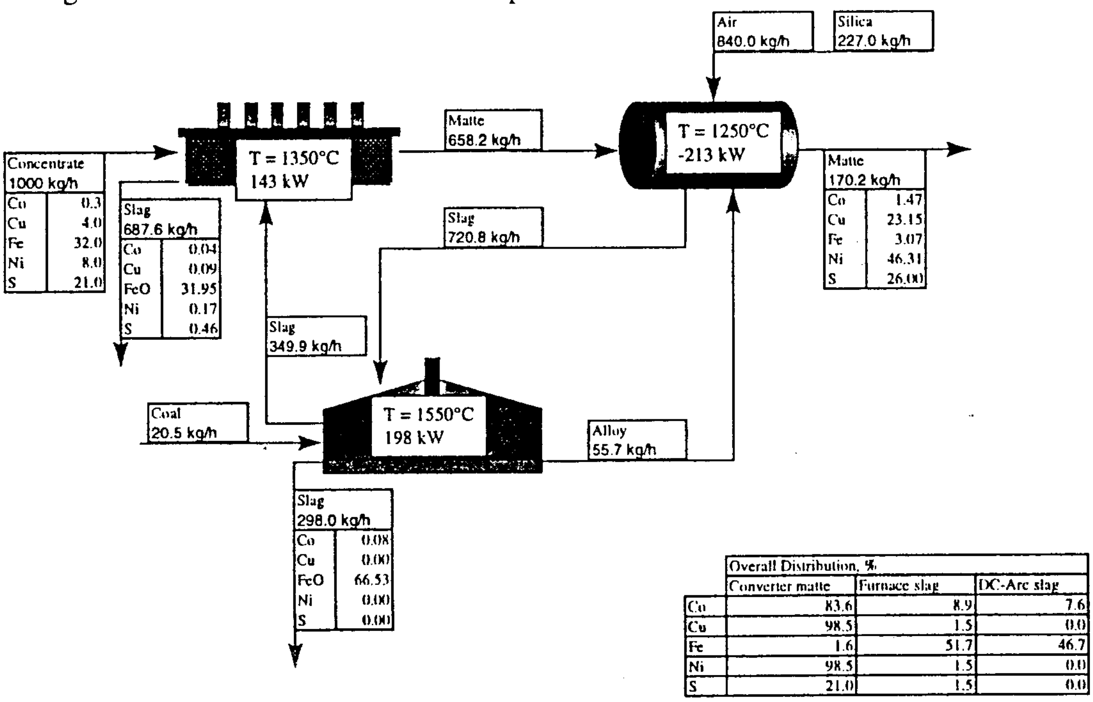



| | Overall Distribution, % | |
|---|---|---|
| | Converter matte | DC-Arc slag |
| Co | 92.0 | 8.1 |
| Cu | 100.0 | 0.0 |
| Fe | 1.6 | 98.4 |
| Ni | 100.0 | 0.0 |

**Figure 8 Flowsheet for Option 7**

## Option 8 Converter slag in DC-arc furnace and Peirce-Smith converter, partial recycle

A DC-arc slag-cleaning furnace treats the liquid converter slag. The alloy produced in the slag-cleaning furnace is treated in an existing converter. Some of the slag from the slag-cleaning furnace is recycled back to the primary furnace, the rest is discarded. The slag from the primary furnace is dumped. Figure 9 contains the flowsheet for Option 8.




| | Overall Distribution, % | | |
|---|---|---|---|
| | Converter matte | Furnace slag | DC-Arc slag |
| Co | 83.6 | 8.9 | 7.6 |
| Cu | 98.5 | 1.5 | 0.0 |
| Fe | 1.6 | 51.7 | 46.7 |
| Ni | 98.5 | 1.5 | 0.0 |
| S | 21.0 | 1.5 | 0.0 |

**Figure 9 Flowsheet for Option 8**

# RESULTS AND DISCUSSION

The important aspects of the processes simulated are summarized in tabular form to facilitate a simple comparison of the flowsheets options considered. The processes can be compared on the bases of product grade, cobalt recovery, and theoretical energy requirements.

## Matte and alloy analyses

The analyses and mass flowrates of the converter matte are given in Table 3. It can be seen that there is little variation in both product grade and mass flowrate.

**Table 3 Analyses and flowrates of converter matte**

| | Base | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 | Option 6 | Option 7 | Option 8 |
|---|---|---|---|---|---|---|---|---|---|
| **Co, %** | 1.24 | 1.24 | 0.96 | 0.91 | 1.24 | 0.96 | 0.90 | 1.60 | 1.47 |
| **Cu, %** | 23.23 | 23.23 | 23.33 | 23.33 | 23.23 | 23.33 | 23.33 | 23.13 | 23.15 |
| **Fe, %** | 3.01 | 3.01 | 3.01 | 3.03 | 3.01 | 3.01 | 3.03 | 3.01 | 3.07 |
| **Ni, %** | 46.48 | 46.48 | 46.71 | 46.72 | 46.48 | 46.71 | 46.71 | 46.26 | 46.31 |
| **S, %** | 26.04 | 26.04 | 25.99 | 26.02 | 26.04 | 25.99 | 26.03 | 26.00 | 26.00 |
| Flowrate (kg/h) | 169.4 | 169.4 | 160.2 | 160.2 | 169.4 | 160.2 | 160.3 | 172.9 | 170.2 |

Table 4 gives the analyses and mass flowrates of the alloy produced from the slag-cleaning process, from the TBRC (if present), or from the DC-arc furnace directly. For Options 7 and 8, the only product is the Peirce-Smith converter matte.

**Table 4 Analyses and flowrates of the DC-arc furnace and TBRC alloys**

| | DC-arc furnace alloy | | | TBRC alloy | | |
|---|---|---|---|---|---|---|
| | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 | Option 6 |
| **Co, %** | 1.50 | 2.42 | 2.26 | 12.75 | 8.73 | 8.17 |
| **Cu, %** | 1.31 | 4.30 | 4.19 | 12.62 | 15.97 | 16.11 |
| **Fe, %** | 87.48 | 79.24 | 79.89 | 30.80 | 30.25 | 30.34 |
| **Ni, %** | 2.57 | 8.47 | 8.22 | 24.75 | 31.46 | .31.65 |
| **S, %** | 7.08 | 5.54 | 5.42 | 19.08 | 13.60 | 13.75 |
| Flowrate, kg/h | 49.1 | 46.6 | 47.9 | 5.1 | 12.6 | 12.5 |

From Table 4 it can be seen that the TBRC alloys have much lower iron contents and flowrates, as intended. Although Options 1 and 4 have lower cobalt mass flowrates in the alloy produced, more cobalt is recovered in the converter matte than for the other slag-cleaning options.

The analyses and mass flowrates of the matte produced in the primary furnace are given in Table 5.

**Table 5 Analyses and flowrates of furnace matte**

| | Base | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 | Option 6 | Option 7 | Option 8 |
|---|---|---|---|---|---|---|---|---|---|
| **Co, %** | 0.60 | 0.60 | 0.46 | 0.43 | 0.60 | 0.46 | 0.43 | 0.68 | 0.46 |
| **Cu, %** | 6.45 | 6.45 | 6.11 | 6.10 | 6.45 | 6.11 | 6.13 | 6.49 | 5.99 |
| **Fe, %** | 47.61 | 47.61 | 48.77 | 49.27 | 47.61 | 48.77 | 49.05 | 47.25 | 50.16 |
| **Ni, %** | 12.89 | 12.89 | 12.22 | 12.20 | 12.89 | 12.22 | 12.26 | 12.97 | 11.97 |
| **S, %** | 32.46 | 32.46 | 32.08 | 32.00 | 32.46 | 32.08 | 32.14 | 32.61 | 31.42 |
| Flowrate (kg/h) | 643.1 | 643.1 | 644.7 | 645.9 | 643.1 | 644.7 | 642.8 | 639.2 | 658.2 |

It can be seen that the composition of the furnace matte is not greatly influenced by changes in the slag recycle streams to the furnace. The mass of matte produced is also fairly constant for the different options explored.

## Mass flowrates of streams

The mass flowrates of the different slag, matte, and alloy streams are summarized in Table 6.

**Table 6 Mass flowrates (kg/h) of the slag, matte, and alloy streams**

| | Base | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 | Option 6 | Option 7 | Option 8 |
|---|---|---|---|---|---|---|---|---|---|
| **Furnace slag** | 975.3 | 975.3 | 360.5 | 938.4 | 975.3 | 360.5 | 1017.2 | 1079.0 | 687.6 |
| **Furnace matte** | 643.1 | 643.1 | 644.7 | 645.9 | 643.1 | 644.7 | 642.8 | 639.2 | 658.2 |
| **Converter slag** | 588.7 | 588.7 | 604.7 | 610.8 | 588.7 | 604.7 | 605.4 | 672.1 | 720.8 |
| **Converter matte** | 169.4 | 169.4 | 160.2 | 160.2 | 169.4 | 160.2 | 160.3 | 172.9 | 170.2 |
| **DC-arc slag** | | 915.7 | 543.8 | 548.2 | 996.4 | 611.1 | 610.8 | 1013.5 | 298.0<br>349.9* |
| **DC-arc alloy** | | 49.1 | 46.6 | 47.9 | 52.6 | 53.9 | 52.0 | 53.5 | 55.7 |
| **TBRC slag** | | | | | 85.1 | 76.2 | 73.0 | | |
| **TBRC alloy** | | | | | 5.1 | 12.6 | 12.5 | | |

* 54 % of the DC-arc furnace slag was recycled to the primary furnace, the rest was discarded.

The mass of slag produced in the primary furnace depends mainly on the presence of the slag recycle from either the converter or the DC-arc furnace (as expected). The mass of furnace matte produced did not differ by more than 0.6 % (compared with the base case), except for Option 8, where 2.4 % more matte was produced.

The biggest change in the mass of slag produced in the converter is for Options 7 and 8, where the DC-arc furnace alloy was also upgraded in the existing converter. For Options 2, 3, 5, and 6, where the converter slag was cleaned in the DC-arc furnace, the mass of matte produced was approximately 5.5 % less than any of the other options.

The masses of DC-arc furnace alloy and slag produced were influenced by the type of slag (furnace or converter) being cleaned in the DC-arc furnace, and by the presence of a TBRC slag recycle stream.

When cleaning the primary furnace slag in the DC-arc furnace (Options 1, 4, and 7), more slag was produced (and treated) than in Options 2, 3, 5, 6, and 8, where the converter slag was cleaned in the DC-arc furnace.

## Cobalt recovery

Table 7 shows the recoveries of cobalt, copper, iron, and nickel from the incoming concentrate reporting to the matte and/or alloy products.

**Table 7 Recoveries of cobalt and other metals**

| | Base | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 | Option 6 | Option 7 | Option 8 |
|---|---|---|---|---|---|---|---|---|---|
| **Co, %** | 69.8 | 94.3 | 89.1 | 84.6 | 91.5 | 88.0 | 82.2 | 92.0 | 83.6 |
| **Cu, %** | 98.4 | 100.0 | 98.5 | 98.5 | 100.0 | 98.5 | 98.5 | 100.0 | 98.5 |
| **Fe, %** | 1.6 | 14.6 | 12.7 | 13.1 | 2.0 | 2.6 | 2.6 | 1.6 | 1.6 |
| **Ni, %** | 98.4 | 100.0 | 98.5 | 98.5 | 100.0 | 98.5 | 98.5 | 100.0 | 98.5 |

The 100 % recoveries of nickel and copper for Option 1, 4, and 7 would obviously not be attained in actual practice, as there would be some degree of alloy entrainment in the DC-arc furnace slag, as well as other handling losses.

The masses of elemental cobalt (probably present as CoO in the slags) entering and leaving the leaving the system are shown in Table 8.

**Table 8 Masses of cobalt (kg/h) entering and leaving the system**

| | Base | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 | Option 6 | Option 7 | Option 8 |
|---|---|---|---|---|---|---|---|---|---|
| <u>In</u> | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| <u>Out</u> | | | | | | | | | |
| Slag* | 0.91 | 0.16 | 0.33 | 0.46 | 0.25 | 0.36 | 0.54 | 0.24 | 0.49 |
| Matte / Alloy** | 2.09 | 2.83 | 2.67 | 2.54 | 2.75 | 2.64 | 2.47 | 2.76 | 2.51 |

* All slags leaving the system.

** All mattes and alloy leaving the system.

As can clearly be seen in Table 7 and Table 8, the best cobalt recoveries can be obtained in Options 1, 4, and 7, when treating the slag produced in the primary furnace and keeping the converter slag recycle intact. If the converter slag needs to be treated, it is better to break the slag recycle to the furnace, as shown by 89 % recovery for Option 2 compared with 85 % for Option 3. Breaking the slag recycle to the furnace could, however, possibly affect the performance of the furnace.

Furthermore, it can be seen in Table 7 that the additional converter actually reduced the cobalt recovery for each of the different flowsheets considered (Option 1 and 4, Option 2 and 5, and Option 3 and 6). If the hydrometallurgical stage can tolerate alloys with a high iron content (with some silicon present), the use of an additional converter might not be necessary. If the hydrometallurgical stage cannot tolerate such high levels of iron in the alloy, the DC-arc furnace alloy can be upgraded utilizing an existing converter. Utilizing an existing converter does not have a noticeable effect on the cobalt recoveries (91.5 % for Option 4 with a TBRC compared with 92 % for Option 7). It should be noted that if the Peirce-Smith converter matte is blown down to very low levels of iron, the slag recycle load to the primary smelting furnace may become excessive.

## <u>Energy requirements</u>

The theoretical energy requirements (without any losses, in kWh per ton of concentrate fed) for each of the units for each flowsheet considered are given in Table 9.

**Table 9 Energy requirements of each furnace, kWh/t concentrate**

| | Base | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 | Option 6 | Option 7 | Option 8 |
|---|---|---|---|---|---|---|---|---|---|
| Six-in-line | 262 | 262 | 149 | 174 | 262 | 149 | 185 | 288 | 143 |
| DC-arc | | 172 | 166 | 169 | 186 | 181 | 180 | 193 | 198 |
| Total | 262 | 434 | 315 | 343 | 448 | 330 | 365 | 481 | 341 |

By breaking the slag recycle in Options 2 and 5, the energy requirements for the furnace are reduced by 43%, from 262 kW to 149 kW. By treating the converter slag and recycling the DC-arc furnace slag to the primary furnace (Options 3 and 6), the energy requirements for the furnace are also affected. This can be attributed to the fact that the DC-arc furnace slag was transferred at 1400 °C to the furnace, while the converter slag was recycled at 1100 °C (Options 1 and 4).

The energy requirement for the DC-arc furnace is influenced only by the method of upgrading the alloy produced in the DC-arc furnace. Upgrading the produced alloy in a TBRC and recycling the TBRC slag to the DC-arc furnace increases the energy requirement for the DC-arc furnace by approximately 8 %.

The total energy requirement should not be interpreted simplistically, but weighed against increased base metal recoveries (primarily cobalt).

## CONCLUSIONS

1. Cobalt recoveries are maximized in the case of the treatment of primary furnace slag (Options 1, 4, and 7). Higher recoveries are obtained from the treatment of primary furnace slag, as opposed to converter slag. This is additionally attractive, as existing plant operations would be minimally affected.

2. Upgrading of the alloy from the slag-cleaning furnace, using a blowing step, has a negative effect on the overall recovery of cobalt. However, some upgrading may be advantageous for more economical hydrometallurgical processing of the alloy. It may be possible to carry out the upgrading step in an existing Peirce-Smith converter, without disrupting converter scheduling.

3. Although additional electrical energy is required for slag-cleaning, the cost is more than offset by the additional cobalt recovery.

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