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# Investigation of Ferrosilicon Losses in the Dense-Medium Separation Circuit at the Kamfundwa Plant, Kambove Territory, Haut-Katanga Province, Democratic Republic of Congo

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**ABSTRACT**

Ferrosilicon (FeSi) consumption at the Kamfundwa Plant, Democratic Republic of Congo, has been found to be excessive, averaging 0.7 kg/ton of ore processed. This high consumption significantly increases operating costs and highlights inefficiencies in the dense-medium separation (DMS) circuit. The present study investigates and quantifies ferrosilicon losses within the circuit and explores potential optimization strategies.

Experimental tests were conducted to identify loss points in the DMS circuit, with ferrosilicon analyzed using magnetic methods. Control campaigns revealed that most losses—99.55%—occurred in the effluent from the magnetic separator, while smaller proportions were recorded in the reject screen (0.176%) and concentrate screen rejects (0.265%).

These findings demonstrate that the magnetic separator is the critical source of ferrosilicon losses, underscoring the need for targeted process improvements. Addressing this inefficiency could substantially reduce FeSi consumption, lower operational costs, and enhance the overall performance of the separation process at the Kamfundwa Plant.

**Keywords:** Ferrosilicon – Gravimetric concentration – Magnetic separation process – Density – Dense medium.

**French version**

La consommation de ferrosilicium (FeSi) à l’usine de Kamfundwa, en République Démocratique du Congo, s’avère excessive, atteignant en moyenne 0,7 kg/tonne de minerai traité. Cette consommation élevée augmente considérablement les coûts d’exploitation et révèle des inefficacités dans le circuit de

séparation dense (DMS). La présente étude vise à évaluer et quantifier les pertes de ferrosilicium dans ce circuit, tout en proposant des stratégies d'optimisation.
Des essais expérimentaux ont été réalisés afin d'identifier les points de perte du circuit DMS, avec une analyse du ferrosilicium effectuée par des méthodes magnétiques. Les campagnes de contrôle ont montré que 99,55 % des pertes de FeSi proviennent de l'effluent du séparateur magnétique, tandis que des proportions plus faibles ont été observées au niveau du crible de rejet (0,176 %) et des rejets du crible de concentré (0,265 %).
Ces résultats démontrent que le séparateur magnétique constitue la principale source de pertes de ferrosilicium, soulignant la nécessité d'améliorations ciblées. La réduction de ces inefficacités permettrait de diminuer la consommation de FeSi, d'abaisser les coûts opérationnels et d'améliorer la performance globale du processus de séparation à l'usine de Kamfundwa.

**List of Abbreviations**

- DMS **:** Dense Medium Separation.
- EMT: Metallurgical Studies.
- GCM: General of Quarries and Mines.
- HMS: Heavy Medium Separation .
- K'DWA: Kamfundwa.
- K'VE: Kambove.
- KVC: Kombove's concentrator.
- RI: Rust Index.
- RM: Mining Backfill (Ore Backfill).
- Sep Mag: Magnetic Separator.
- SNEL: National Electricity Company.
- TL: Washing Rate.
- TS: Dry Ton.

## 1. INTRODUCTION

Dense medium separation (DMS) is a process in which particles are separated according to density. A suspension of defined density is prepared, allowing lighter particles (*floats*) to rise and heavier particles (*sinks*) to settle [1]. The fractions are then collected for further processing. The medium typically consists of water mixed with ferrosilicon or magnetite, with a specific gravity adjusted between valuable minerals and gangue materials [2–4].

DMS is widely applied to upgrade ores such as coal, iron, titanium, chrome, manganese, tin, and tungsten, and is also used for minerals including fluorite, magnesite, and sylvite. Particle size processed varies with equipment, generally between 10 mm and 20 mm [5]. The suspension must maintain stability and fluidity to behave as a Newtonian medium [6].

At the HMS Kamfundwa Plant in Kambove, the ore treated consists mainly of copper and cobalt, with mineralization predominantly oxidized (95%) and associated with siliceous gangue. Dolomitic oxides are relatively low (5%). Gécamines studies since 2011 estimate reserves at approximately 310,000 tons of copper [7].

The use of HMS is justified by the lighter gangue minerals—quartz (d = 2.65), talc (d = 2.75), dolomite (d = 2.85), and limonite (d = 2.7–4.3)—compared to copper minerals such as malachite and azurite (d = 3.6–4.1). HMS thus removes large quantities of gangue upstream, facilitating grinding, leaching, and flotation, and reducing time, energy, and costs [8].

An evaluation of ferrosilicon consumption revealed excessive usage of 0.7 kg/ton of ore processed, significantly increasing operating costs. Typically, acceptable silicon content ranges between 14–16%, with densities of 2.5–4.0 [9]. This study investigates ferrosilicon losses in the DMS circuit of the Kamfundwa Plant, quantifies losses at each exit point, and evaluates associated costs over six months.

## 2. MATERIALS AND METHODS

### 2.1. Study area

The Kamfundwa Mine (also known as Kamoya South II Mine; French: Mine Kamoya Sud II) is one of Gécamines' operations located near Kambove, approximately ten kilometers north of the Kamoya mining district in the Democratic Republic of Congo. As of 2008, its annual production capacity was reported at 400,000 tons of copper and 48,000 tons of cobalt in ore. The mine's coordinates are 10°48′54″S, 26°35′19″E (between 10°48′ and 10°49′30″ South latitude, and 26°34′ and 26°15′30″ East longitude).

### 2.2. *Materials and chemicals*

Chemical and mineralogical analyses were performed using a binocular optical microscope and an inductively coupled plasma mass spectrometer (ICP-MS). All analyses were conducted at the metallurgical laboratory of Gécamines Panda in Likasi, Democratic Republic of Congo.

### *2.3. Methods*

Samples were collected at four different points: three mill outlets and one inlet. At the feed level of the DMS, the samples consisted of crushed solid ore. At the outlets, DMS concentrates were also obtained in solid form. Solid samples were taken at the DMS discharge, while at the magnetic separator effluent, the sample was collected in pulp form.

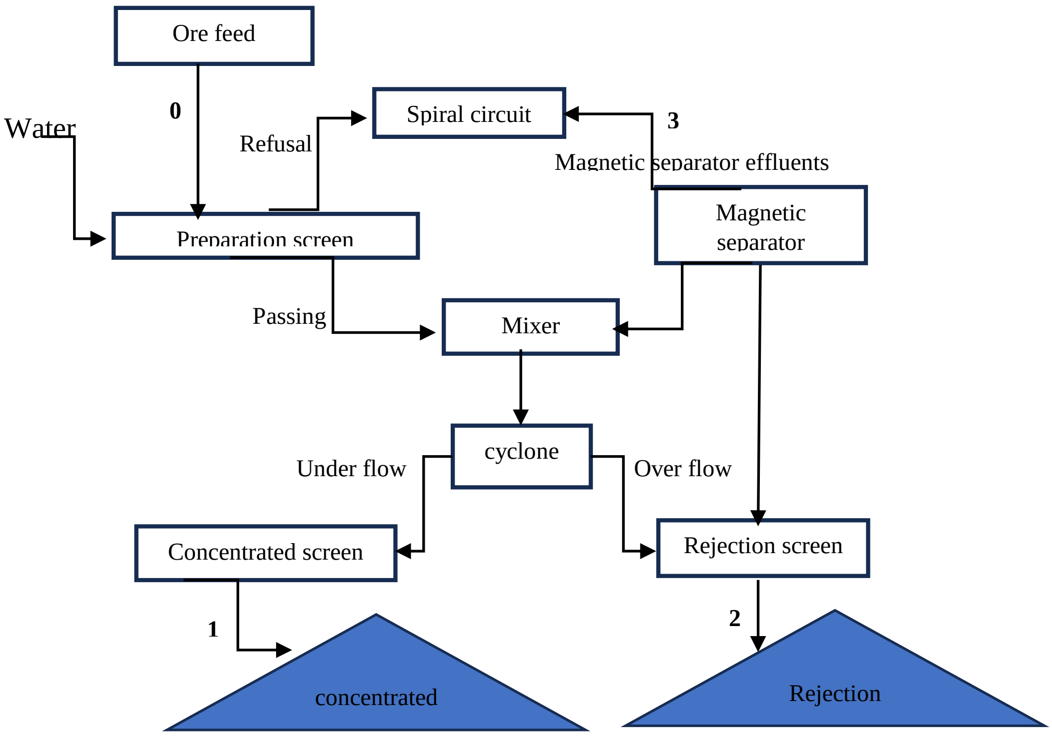


**Figure 1entry and exit points of the DMS/ kamfundwa circuit [10]**

**a) Sampling at the DMS Feed, Concentrate, and Discharge:**

- Approximately 300 g of copper ore samples were collected at two-hour intervals.
- After collection, the individual samples were combined to form a composite sample for mapping.
- The composite sample was then oven-dried for 24 hours at 105 °C.
- Finally, a total of 6,000 g was weighed for testing.

**b) Sampling of Magnetic Separator Effluents:**

- One liter of effluent sample was collected and allowed to settle.
- The sample was then filtered and oven-dried for 24 hours at 105 °C.
- A portion weighing 17 g was prepared for testing.
- Additionally, one liter of pulp was taken from the effluent.
- Its density was measured, after which it was left to settle for eight hours.
- The sample was filtered to separate solids from water, dried in the oven, and the solids were weighed.
- A magnet was passed through the dried material to recover ferrosilicon.
- Any material adhering to the magnet was carefully scraped off and weighed, providing an estimate of the ferrosilicon content.
- The remaining material was classified as non-ferrosilicon.

### 2.3.1. Granulometric analysis of ore and ferrosilicon

Particle size analysis was conducted using Tyler sieves. A total of 1,000.6 g of crushed, dry ore was used to determine the particle size distribution, employing 14 Tyler sieves with apertures of 19,000; 12,700; 6,750; 3,350; 840; 300; 212; 150; 106; 75; 53; 45; 38; and <38 µm.

- A mass of 500 g of ferrosilicon and ore was weighed.
- The samples were passed through the sieve stack.
- The rejects from each sieve were weighed, and both the total sample mass and cumulative rejects were recorded.
- The cumulative rejection percentages obtained were entered on the test sheet.
- Finally, the percentage passing through each sieve was calculated.

### 2.3.2. Laboratory analysis of ore and ferrosilicon

The chemical analysis of F270D ferrosilicon was performed at the EMT/Kambove laboratory using an atomic absorption spectrometer (AAS), while the ore samples were analyzed at the Gécamines Likasi laboratory using an inductively coupled plasma mass spectrometer (ICP-MS).

## 3. RESULTS AND INTERPRETATION

The results of the analyses carried out between April 2018 and March 2019 are presented as follows: Table 1 shows the mineralogical composition of the sample; Table 2, the chemical composition of the sample; Table 3, the particle size distribution of the sample; Table 4, the chemical analysis of ferrosilicon (FeSi); Table 5, the factory standards; Table 6, the results of particle size analysis of FeSi; Table 7, the evaluation of FeSi losses from the DMS circuit; and Table 8, the evaluation of loss analysis.

### 3.1. Mineralogical analysis results of the sample

Analysis of the samples under a binocular microscope revealed the presence of copper, calcium, and magnesium. The results are presented in Table 1.

**Table 1: Mineralogical composition of the sample**

| Mineralogical class | Mineral species | Chemical formula | Density | Elements to be valued |
|---|---|---|---|---|
| Carbonates | - Malachite<br>- Azurite | - $Cu_2((OH)_2CO_3)$<br>- $Cu_3((OH)CO_3)_2$ | - 3 to 4<br>- 3.8 | - Cu<br>- Cu |
| Oxides | - Calcium oxide<br>- Magnesium oxide | - CaO<br>- MgO | | |
| Silicate | - Quartz | - $SiO_2$ | - 2.6 | - |

The results in Table 1 revealed that the copper, concentrated at the Kamfundwa Plant, is in the form of carbonate. According to the Gécamines standard, which states that if the ratio of the percentage of total copper to the percentage of soluble lime is greater than 15%, this means that the nature of the gangue in the sample is siliceous. [11]

According to the calculations of the results of: $\frac{2{,}85\ (Cu\ tot)}{0{,}14\ (CaO\ sol)} = 20{,}35\%$ ; the examination of this calculation indicates a siliceous gangue because the ratio is greater than 15%.

The results presented in Table 1 revealed that the copper concentrated at the Kamfundwa Plant occurs in the form of carbonate. According to the Gécamines standard, if the ratio of total copper percentage to soluble lime percentage exceeds 15%, the gangue in the sample is classified as siliceous [11]. Based on the calculations,

$\frac{2{,}85\ (Cu\ tot)}{0{,}14\ (CaO\ sol)} = 20{,}35\%$ ; Since this ratio is greater than 15%, the gangue is identified as siliceous.

### 3.2.Chemical Composition of the Sample at the DMS Circuit Feed Level

The results presented in Table 2 reveal the presence of copper, cobalt, calcium, manganese, magnesium, aluminum, and iron in the samples.

**Table 2: Chemical composition of the sample at the DMS circuit supply level**

| Elements | Contents (%) | Elements | Contents (%) |
|---|---|---|---|
| **$Cu_{tot}$** | 2.85 | $_{Total}$ MgO | 4.87 |
| **$Cu_{sol}$** | 2.07 | $MgO_{soil}$ | 0.15 |
| **$Co_{total}$** | 0.27 | $SiO_2$ | 73.72 |
| **$Co_{ground}$** | 0.20 | $Al_2O_3$ | 2.56 |
| **$_{Total}$ CaO** | 0.79 | Fe | 2.36 |
| **$CaO_{sol}$** | 0.14 | PF | 4.68 |
| **MnO** | 0.22 | | |

Table 2 shows that copper is present mainly in soluble form. It also provides information on the presence of iron in the feed.

### 3.3.Particle size distribution of the sample

The results of the particle size analysis are presented in Table 3.

**Table 3particle size distribution**

| Fraction (µm) | | Mass (g) | Mass distribution (%) | Cumulative refusals (%) | Cumulative passers-by (%) |
|---|---|---|---|---|---|
| | +19000 | 266.00 | 26.58 | 26.58 | 73.42 |
| - 19000 | +12700 | 237.00 | 23.69 | 50.27 | 49.73 |
| **-12700** | +6750 | 218.00 | 21.79 | 72.06 | 27.94 |
| -6750 | +3350 | 151.00 | 15.09 | 87.15 | 12.85 |
| -3350 | +1650 | 68.10 | 6.81 | 93.95 | 6.05 |
| -1650 | +840 | 46.70 | 4.67 | 98.62 | 1.38 |
| -840 | +300 | 1.60 | 0.16 | 98.78 | 1.22 |
| -300 | +212 | 1.00 | 0.10 | 98.88 | 1.12 |
| -212 | +150 | 1.00 | 0.10 | 98.98 | 1.02 |
| -150 | +106 | 1.20 | 0.12 | 99.10 | 0.90 |
| -106 | +75 | 1.70 | 0.17 | 99.27 | 0.73 |
| -75 | +61 | 2.00 | 0.20 | 99.47 | 0.53 |
| -61 | +45 | 2.80 | 0.28 | 99.75 | 0.25 |
| -45 | +38 | 1.40 | 0.14 | 99.89 | 0.11 |
| -38 | | 1.10 | 0.11 | 100.00 | 0.00 |

The results presented in Table 3 reveal that:

- 26.58% of the grains are in the fraction above 19,000 µm;
- 72.04% of the grains fall within the range from −19,000 µm to 840 µm;
- 1.38% of the grains are in the fraction below 840 µm.

Analysis of Table 3 shows that only 72.04% of the feed meets the required specifications. According to the factory standard for the dense medium separation (DMS) circuit, the particle size of the feed should fall within the range of 1,900 µm to 840 µm. The fraction below 840 µm is directed to the spiral circuit, while the fraction above 1,900 µm is re-ground to meet the particle size requirements of either the DMS or spiral feed.

### 3.4.Ferrosilicon used at the KAMFUNDWA plant

The ferrosilicon used during the study period was sourced from South Africa under the designation FeSi 270D, with an iron purity of 83% and a silicon content of 13.9%, as shown in Table 4 [12]. The results of this analysis are reported in Table 4.

**Table 4: Chemical analysis result of FeSi [13]**

| Sample | Fe% | If% | Cu% | Mn% | Pb ppm | Zn ppm |
|---|---|---|---|---|---|---|
| **270D** | **83** | **13.9** | **0.19** | **0.02** | **67** | **88** |

The concentration of iron in sample 270D is 83%, while the silicon content is approximately 14%. This composition complies with the standards required for use in gravimetric concentration, as indicated in Table I of the appendices [14, 15]. The granulometric analysis of ferrosilicon (FeSi) is presented in Table 5. Examination of the results shows that the ferrosilicon fed at Kamfundwa has a $D_{80}$ (i.e., the particle size at which 80% of the material passes through the sieve) between 45 µm and 53 µm, which fully meets the factory design requirements, as shown in Table 5.

**Table 5: FeSi standards of the DMS plant [16]**

| FERROSILICON STANDARDS FOR DMS | |
|---|---|
| Design recommendation | 1.3 kg of ferrosilicon per tonne of ore fed to DMS |
| Ferrosilicon use according to design | Iron at 80-82%; silicon 14 to 16% |
| Recommended grain size according to design | Less than 0.8mm; Mesh of screens used in DMS 0.8mm |

Table 6 gives the results of the granulometric analysis of ferrosilicon:

**Table 6: Results of particle size analysis of FeSi**

| **Sieve size (µm)** | **Mass (g)** | **Mass distribution (%)** | **(%) cumulative refusals** | **(%) cumulative passing** |
|---|---|---|---|---|
| 150 | 0.8 | 0.16 | 0.16 | 99.84 |
| 106 | 2.98 | 0.58 | 0.74 | 99.26 |
| 75 | 10.2 | 2,041 | 2.8 | 97.21 |
| 53 | 49.3 | 9.86 | 12.6 | 87.35 |
| 45 | 162.8 | 32.57 | 45.2 | 54.78 |
| 38 | 96.7 | 19.35 | 64.6 | 35.43 |
| -38 | 177 | 35.49 | 100 | 0 |
| | 499.73 | | | |

### 3.5. Results of the control campaign

The control campaign consisted of identifying magnetic iron in the feed, evaluating ferrosilicon losses in the rejects from the concentrate screen, in the reject screens, and in the effluents from the magnetic separator, as well as assessing the specific consumption of ferrosilicon at the plant level.

#### *3.5.1. Results of the evaluation of the specific consumption of FeSi at the Kamfundwa plant*

The results of the evaluation of the specific consumption of ferrosilicon (FeSi) at the plant are shown in Figure 2.

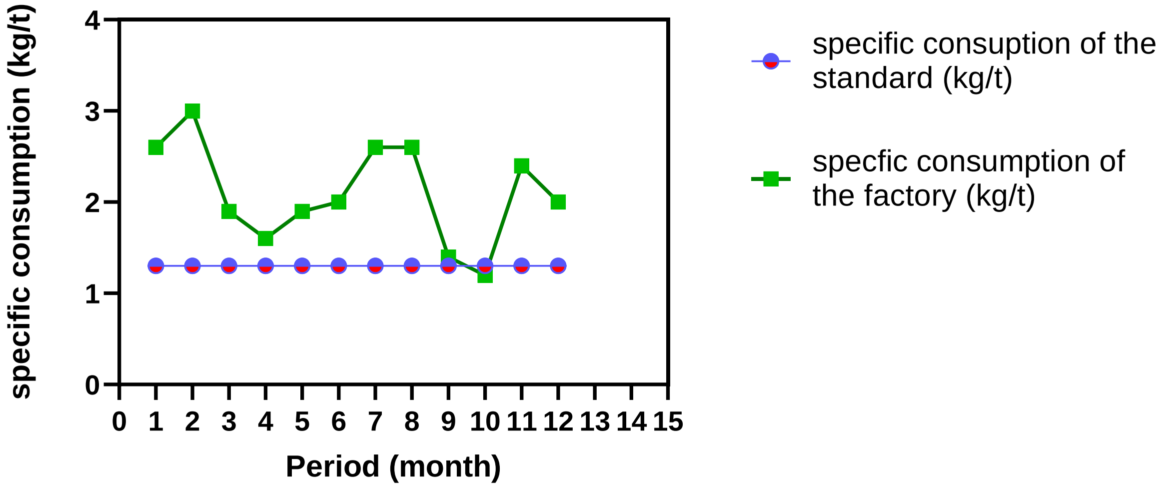


**Figure 2: Plant evaluation on FeSi consumption**

Figure 2 shows that the plant's average ferrosilicon consumption over 12 months is 2.0 kg/ton higher than the design specification, which is set at 1.3 kg/ton. The exception is the month of February, when consumption was reduced due to plant shutdowns. Operating with a specific consumption above the design level resulted in the use of 696,250 kg of ferrosilicon—247,358.71 kg more than the design consumption—which directly impacts the plant's operating costs.

### *3.5.2. Results of the evaluation of ferrosilicon losses in the DMS circuit*

The results of the FeSi loss assessment in the DMS circuit are reported in Table 7. Examination of the results shows the presence of magnetic material in the DMS concentrate, in the DMS discharge, and in the effluents from the magnetic separator, while the feed to the DMS circuit contains none. The magnetic material identified is ferrosilicon.

Recovery of the medium (ferrosilicon) indicates that, after separation, part of the medium is recovered by simple draining and recycled into the concentration circuit (correct medium tank). The other portion, resulting from the washing of the flotation-dipping agents (diluted medium tank), is reconcentrated magnetically, demagnetized, and adjusted in density before being returned to the working circuit. Since the medium is recovered and reinjected into the circuit, it is unlikely that ferrosilicon will be found in the DMS concentrate, the DMS reject, or in the effluents of the magnetic separator.

**Table 5: Results of evaluation of FeSi losses in the DMS circuit**

| Sampling date | **Sampling point 0** | | **Sampling point 1** | | **Sampling point 2** | | **Sample point 3** | |
|---|---|---|---|---|---|---|---|---|
| | DMS power supply | | DMS Concentrate | | DMS Rejection | | Effluents Magnetic Separator | |
| | Sample mass (g) | Mass of magnetic matter (g) | Sample mass (g) | Mass of magnetic matter (g) | Sample mass (g) | Mass of magnetic matter (g) | Sample mass (g) | Mass of magnetic matter (g) |
| **05/27/2019** | 1000 | 0 | 1000 | 0.25 | 1000 | 0.65 | 3.8 | 1;2 |
| **05/28/2019** | 1000 | 0 | 1000 | 0.43 | 1000 | 0.5 | 4.1 | 0.76 |
| **05/29/2019** | 1000 | 0 | 1000 | 0 | 1000 | 0.57 | 3 | 0.42 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **05/30/2019** | 1000 | 0 | 1000 | 0.5 | 1000 | 0.8 | 0 | 0 |
| **06/03/2019** | 1000 | 0 | 1000 | 0.54 | 1000 | 0 | 3;3 | 0.52 |
| **04/06/2019** | 1000 | 0 | 1000 | 0.32 | 1000 | 0.55 | 2.8 | 0.36 |
| **Total mass** | 6000 | 0 | 6000 | 2.04 | 6000 | 3.07 | 17 | 3.26 |
| **% ferrosilicon loss** | | | | 0.051% | | 0.034% | | 19.17% |

Loss analysis allows for the quantification of ferrosilicon losses in the DMS circuit. The results presented in Table 8 show that 99.55% of the ferrosilicon losses in the circuit originate from the magnetic separator.

**Table 6: Loss analysis**

| **Sampling points** | **Ferrosilicon mass (g)** | **Percentage of the amount of ferrosilicon** |
|---|---|---|
| Rejection of the reject screen | 0.034 | 0.176 |
| Discharge from the concentrate screen | 0.0511 | 0.265 |
| Effluent magnetic separator | 19,176 | 99,558 |
| Total | 19,2611 | |

### 3.6.Ferrosilicon loss on plant cost

According to the internal document of Gécamines (HMS document, 2012) [17], ferrosilicon (FeSi) accounts for 22.72%—rounded to 23%—of the treatment cost at the HMS Kamfundwa plant. The same document estimates that FeSi represents 11.36% of the supply cost for the DMS circuit, corresponding to half of the overall supply.

This step therefore consists of determining the optimum FeSi consumption in kilograms per ton of ore processed at the HMS concentrator in Kamfundwa. Given that FeSi consumption has been steadily increasing and reaching values significantly higher than the design specification (1.3 kg of FeSi per ton of ore, at a cost of $3.50), this excess consumption has resulted in additional costs, as detailed in the calculations below.

**Calculation of the quantity of FeSi consumed on average over 12 months**

- **The amount of FeSi consumed was calculated using Equation I**

*Mass of FeSi consumed = dry tonnes fed * mass of FeSi per tonne of ore fed (I )*

*The mass of FeSi consumed = 345301 X 2.0 = 690,602 Kg of FeSi on average over 12 months or 690.602 T of FeSi .*

- **Calculation of cost based on the mass of ore fed**

The cost of fed FeSi is determined using Equation (II):

$$cout\ du\ FeSi\ par\ minerai\ alimenré = \frac{masse\ du\ FeSi\ consommé\ X\ le\ prix\ d'un\ fut\ FeSi}{masse\ du\ minérai\ alimenté} (II)$$

$$\frac{690{,}602\ X\ 2700}{345301} = \$5.4\ per\ ton\ of\ ore\ fed$$

- **Calculation of additional cost**

Equation (III) gives the calculation of the additional cost

$$cout\ suplémentaire\ = \frac{consommation\ du\ FeSi\ (moyenne\ de\ 12mois)}{cout\ du\ FeSi\ par\ tonne\ de\ minerai\ alimenté} (III)$$

$cout\ suplémmentaire\ = \frac{2{,}0}{5{,}4} = \$0.37\ additional\ cost\ which\ is\ due\ to\ the\ loss\ of\ FeSi$

Examination of the calculations in equations (I, II, and III) shows that the cost of ferrosilicon, according to the factory standard, is \$3.50 per ton of ore treated in the concentrator by dense medium, based on a specific consumption of 1.3 kg/t. In comparison, the actual consumption during the 12-month period was 2.0 kg/t, corresponding to a cost of \$5.40 per ton of ore treated, resulting in an additional cost of \$0.37 per ton.

## 4. CONCLUSION

The study of ferrosilicon losses in the DMS circuit at the Kamfundwa Plant shows that, following magnetic separation tests on samples taken at Kambove, 99.36% of the losses occurred in the magnetic separator effluent. These losses have a negative impact on ore processing costs, which average around US \$5.40 per ton. This cost is significantly higher than the initial processing cost planned in the plant design (US \$3.50 per ton). Therefore, an optimization study of ferrosilicon losses is necessary to reduce production costs when using ferrosilicon as a dense medium.

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