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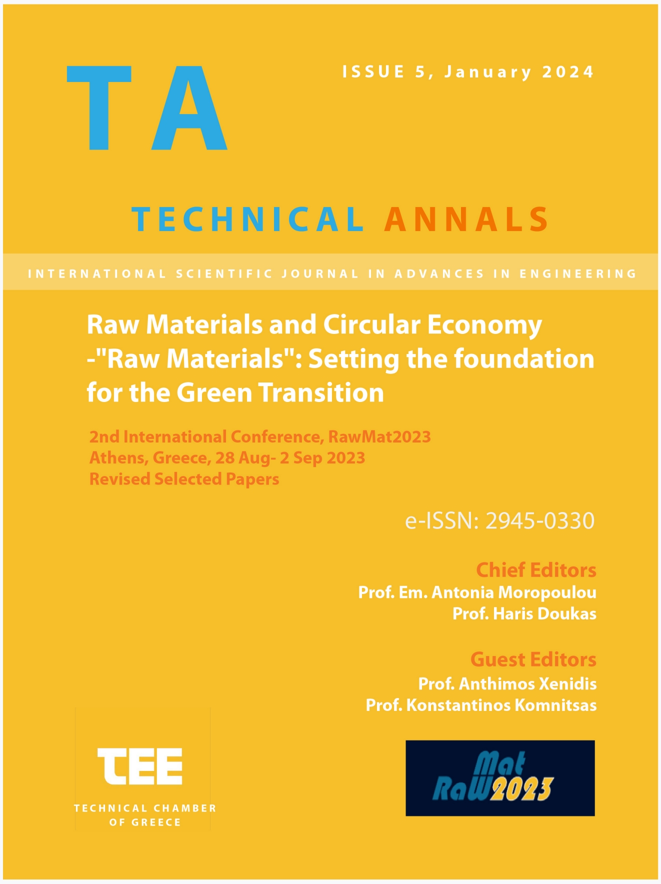

Critical Review of the Metallurgical Operation of the Greek Nickel Industry and Perspectives, based on the recent Industrial Experience on Smelting Reduction Process

Charalabos Zografidis, Konstantinos Betsis, Anthimos Xenidis

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Critical Review of the Metallurgical Operation of the Greek Nickel Industry and Perspectives, based on the recent Industrial Experience on Smelting Reduction Process

Charalabos Zografidis[1], Konstantinos Betsis[2] and Anthimos Xenidis[2]

[1]Hellenic Survey of Geology and Mineral Exploration 1, Spyrou Loui St, Acharnes, 13677 Athens, Greece
[2]National Technical University of Athens, 9, Iroon Polytechniou St., 15780 Athens, Greece
chzografidis@eagme.gr

Abstract. The mining and industrial production of Greek ferronickel industry LARCO have ceased since 30.07.2022. The last LME nickel price crisis, exclusion from bank loaning, extremely high cost of electrical energy, management issues, resulted inter alia, in a prohibitive operational cost. Nevertheless, LARCO faces the challenge of adapting to the demands of a modern industrial operation as well as administration, given that privatization is in progress.
Within this framework, the current paper aims to critically comment on the quite recent industrial data concerning smelting reduction, being presented and analyzed, in order to contribute to the research for optimizing the applied pyrometallurgical process. Based on industrial experience concerning open bath submerged arc electric furnaces, focus is made on the critical factors of raw materials' management, maintenance strategy and a totally new human resources management strategy that should be adopted by a new ownership, so that the optimal techno-economic result of such an investment could be reached. Moreover, taking for granted the need for Ni-rich 'foreign' ores to increase the recovery and reduce the cost of the process, the extent of dependence on Fe-rich domestic ores is investigated, in order a safe and stable operation to be ensured.

Keywords: laterites; ferronickel; optimization, reductive smelting

1 Introduction

Ferronickel (Fe-Ni) with a Ni % analysis among 20 and 40%, and Nickel Pig Iron (NPI), constitute the predominant Nickel Class II category products, which meet an outstanding demand growth since 2006, with a widespread production in China and Indonesia. Nickel demand is still predominantly driven by the stainless steel industry, accounting for almost 70% of the total primary nickel consumption [1]. Furthermore, as seen in Figure 1, the primary nickel production (including Nickel Class I products) reached an outstanding increase of almost 40% within the last three years, taking for granted the forecast that it will overcome 3.370.000 t by the end of 2023 [2], despite the negative challenges of COVID-19 pandemic and the energy crisis in the meantime.

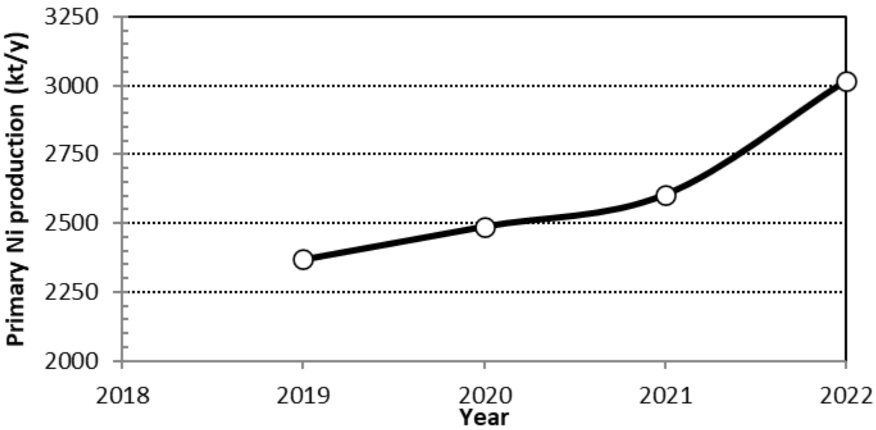

Fig. 1. Primary nickel production evolution

Nevertheless, as seen in Figure 2, the primary nickel production trend in China and Indonesia (C&I) is opposite in comparison with nickel production in Europe (not including Russia). Moreover, it can be clearly seen in Figure 3, that Europe's smelter Fe-Ni production in 2022 faced an enormous 57% decline, which can be safely attributed to the soaring energy costs. More specifically, based on INSG world statistics published, apart from Greece, the smelters' production for Fe-Ni production in Kossovo and Ukraine has been ceased in 2023, while in North Macedonia the production has been declined by 54.2%. The overall primary nickel production in Europe, including the sole nickel sulfide smelter in Finland (Harjavalta) has been declined by over 20% within the last two years.

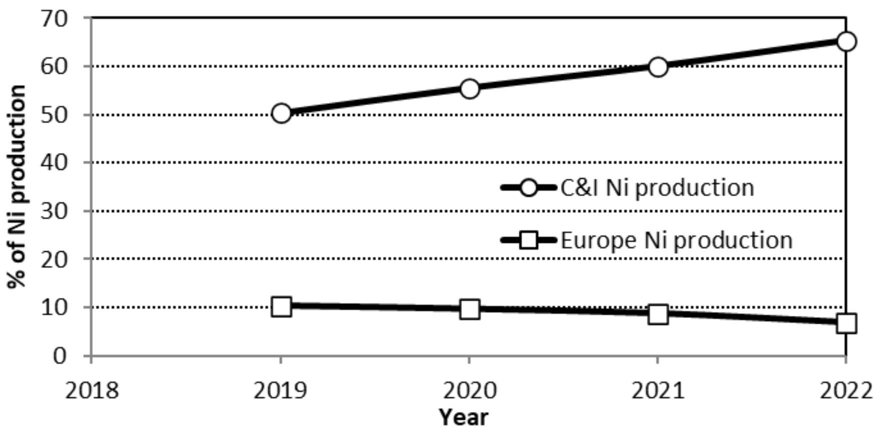

Fig. 2. Ni production as a percentage in China & Indonesia vs Europe

In any case, the forecast for the significant increase of nickel demand for usage in the battery sector within the next 15 years, challenges the European governments, apart from motivating nickel producers with more viable energy supplying prices in order to remain competitive in the Class II nickel production market, to seriously invest in R&D costs for enhancing greenfield projects for the production of nickel-matte or intermediate products, such as nickel sulfate or Mixed Hydroxide Precipitate (MHP). Furthermore, the absolute need for the nickel producers world-wide to alter their operational flowsheets targeting to meet the requirement for products more easily integrated in the lithium ion batteries market, enhance the research efforts for NPI or Fe-Ni conversion to nickel matte or other similar intermediate products, which can be further refined [4]. Within this framework, Hellenic Minerals Ltd. in Cyprus, is in the commissioning state of a Heap Leaching-Solvent Extraction-Crystallizer (HL-SX-CR) unit for $NiSO_4.6H_2O$ production [3].

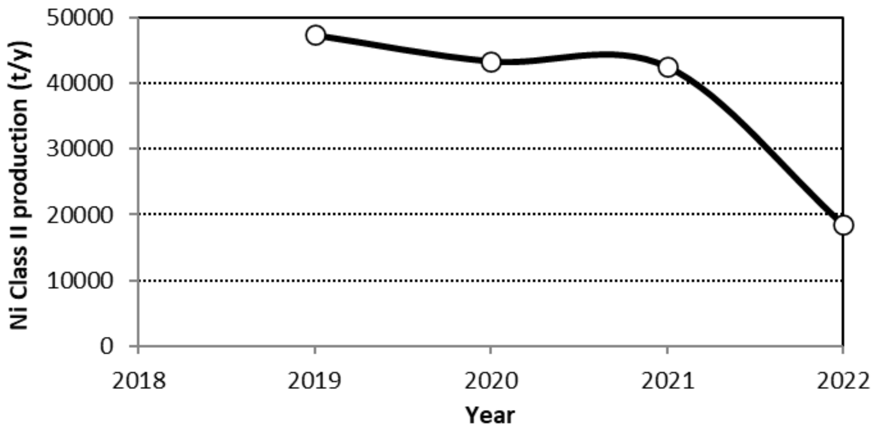

Fig. 3. Europe Ni Class II Production within the period 2019 – 2022

1.1 The Greek Ferronickel Industry

Considering the last 14 years, since 2010, the operation of the Greek Ferronickel Industry LARCO General Mining and Metallurgical Company, passed through many stages. The period 2011 – 2014, when the LME nickel prices as seen in Figure 4 fluctuated among 16.000 – 28.000 USD/ t, the Greek Ferronickel Industry managed to have annual production over 18.000 t of nickel, being historically among the best production performances. The subsequent nickel price crisis period 2015-2020, when the prices reached even 8.000 USD/t, was critical for the further progress of the industrial operation. Key parameters, such as the low nickel price, which resulted in cuts in maintenance and ore mining expenses, the exclusion from bank loaning due to conviction by the European Court for receiving in the past incompatible state aid, and structural and management malfunctions, resulted in a prohibitive operational cost. The extremely high cost of electrical energy (> 200 Euros/MWh) during the last two years, was the ‘deathblow’ for the industrial operation, which finally ceased in 30/7/2022. In the meantime, since 28/2/2020, LARCO is placed under a special administration regime, in accordance with the provisions of article 21 of Law 4664/2020. Furthermore, the Greek Ferronickel industry faces the challenge of restructuring and reoperation in the future, given that privatization procedure is in progress, being in the stage of the acquisition of the company's assets to a joint venture enterprise, after its participation in an international open tender for the transfer of LARCO's assets.

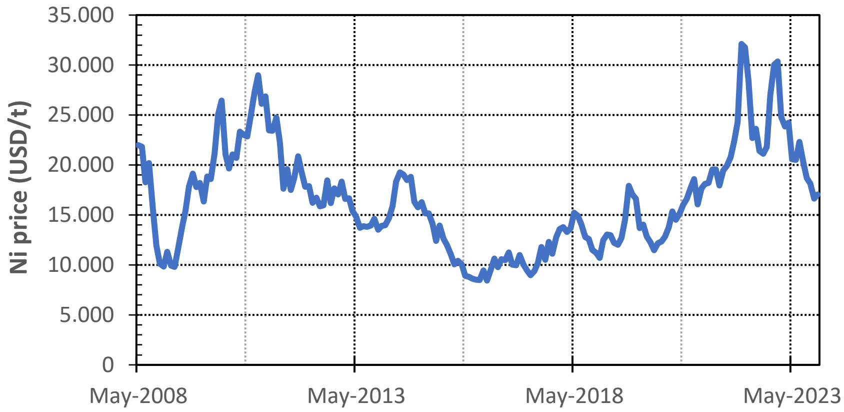

Fig. 4. Ni LME price within the period May 2008 – December 2023

2 Pyrometallurgical Processing of Greek Laterite Ores

Nickel is extracted pyrometallurgically from the domestic laterite (oxidized) ores via the LARCO metallurgical process, having finally succeeded the Krupp-Renn, the LM and the MLar methods, after certain technological and physicochemical modifications [3]. The Larco process [5] having already been presented elsewhere, is based on the application of the Rotary Kiln – Electric Arc Furnace (R/K – E/F) method for the production of Fe-Ni alloy 12-14% which is further enriched to 18-25% Ni in OBM converters.

The Greek nickeliferous laterite ores which comprise the main feed of the R/Ks in the Greek Fe-Ni industry are: Evia island ore (Ore A), Lokrida ore (Ore B) and Kastoria ore (Ore C). Based on the classification of the laterite ores according to their Fe and MgO % content [3], all the different deposits of Ore B are typical B1 type of limonites (Fe > 32%, MgO < 10%). The various deposits of Ore A can be classified among B1 and B2 type of limonites (25% < Fe < 32%, MgO < 10%). On the contrary, Ore C clearly belongs to Intermediate type C2 laterite ore (12% < Fe < 25%, 10% < MgO < 25%).

Temporarily for a short period of time in the past, imported high grade Ni ores were used in the Greek nickel industry, in order to enrich the metallurgical mixture fed in the R/Ks, increase the productivity and decrease the special electrical energy consumption, including: i) Indonesian and Guatemala laterite ores (Ni %>1.6 on a dry basis), which are typical Intermediate type C2 ores, and ii) Turkish laterite ores (Ore T) from different deposits which are typical B2 type of limonites, having significantly higher Ni grade in comparison with the Greek limonitic laterites Ores A&B (Ni %>1.2 on a dry basis).

The case study of the laterite ore material fed in the Greek Fe-Ni industry, can be characterized as extremely rare, taking into consideration that high content of iron in the slag produced in the smelting reduction step (Fe > 28%), results in a lower melting point of the slag than the melting point of Fe-Ni, which means that smelting of the alloy is achieved through slag superheating. Thus, the smelting reduction process with open bath submerged arc E/F operation is method prerequisite for pyrometallurgical processing. Moreover, the critical parameter of SiO_2/MgO content of the Greek laterites (or the slag produced) is greater than 7, while it does not exceed 3 in the case of all the other nickel smelters. Although the Fe/Ni ratio of the Greek laterites is almost 30 (in comparison with not higher than 12 in case of foreign laterites), only about 22% of iron is recovered in the crude Fe-Ni produced in E/Fs, which means that the LARCO method is classified in the low iron reduction category [6].

3 Critical Parameters for the Optimization of smelting reduction of Nickeliferous Laterites

It is clearly deduced by the industrial experience concerning open bath submerged arc electric furnaces, that the factors which constitute the prerequisite for a safe and cost-effective metallurgical process, are presented in Figure 5.

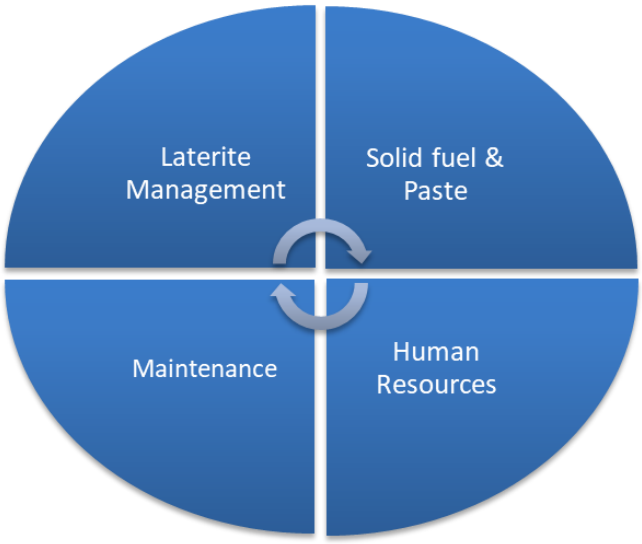

Fig. 5. Critical factors for the optimization of smelting reduction process in the Greek Fe-Ni industry

Within this framework, taken into account that the Greek Fe-Ni industry is on a transitional period, when the reoperation under a new regime, free from the restrictive structural issues of a former public enterprise, should be accompanied by a general management strategy reassessment, the current paper aims to contribute to the former issue, focusing on the step of smelting reduction. Furthermore, the industrial experience of the last 13 years is utilized, in order critical parameters affecting the optimization of smelting reduction to be highlighted, by means of case studies presentation and statistical analysis of operational data.

3.1 Laterite Ores

The Ni % content of the laterite ore mixture (Laterite Mixture – L.M.) fed in the R/K-E/F system of the metallurgical plant is out of doubt the most critical factor affecting the recovery rate and the productivity of the process. The Ni grade of the laterite ore mixture after 2014, has gradually fallen in 2019 (the last year of operation of all the metallurgical equipment of the plant), into level (0.91% on a dry basis) that marginally can be characterized as economic [3] or viable in literature. Additionally, another vital parameter significantly affecting smelting reduction is the difference of iron and SiO_2 content (Fe – SiO_2 %) in the laterite ore mixture and consequently in the slag produced. Its decreasing trend in the last eight years is seen in Figure 6. This is very important, since it intimately affects both: i) the melting point of the laterite mixture, thus the specific energy consumption and ii) the viscosity of the E/F slag, which is related with the intensity of slag foaming phenomena.

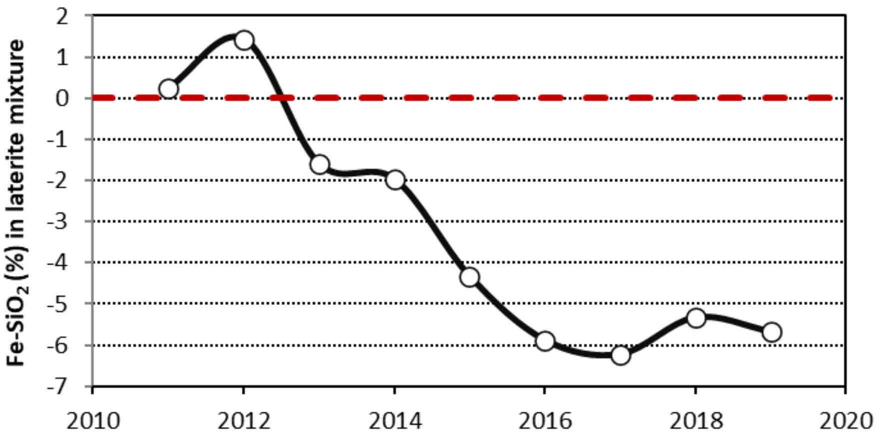

Fig. 6. Difference of iron and SiO_2 content (Fe – SiO_2, %) in the Laterite Mixture (L.M.)

The Operational Index (O.I. %), defined as Uptime × Speedfactor of the E/F equipment, constitutes probably the most critical index of the economic viability of the process, as seen in Figure 7, since it takes into consideration both the parameters: i) time of equipment operation (Uptime) and ii) % utilization of the E/Fs maximum power capability. Moreover, it is deduced that an E/F O.I > 70%, which is a prerequisite for high Ni production, is obtained having ensured an average Fe-SiO_2 (%) content greater than -3% in L.M. feed.

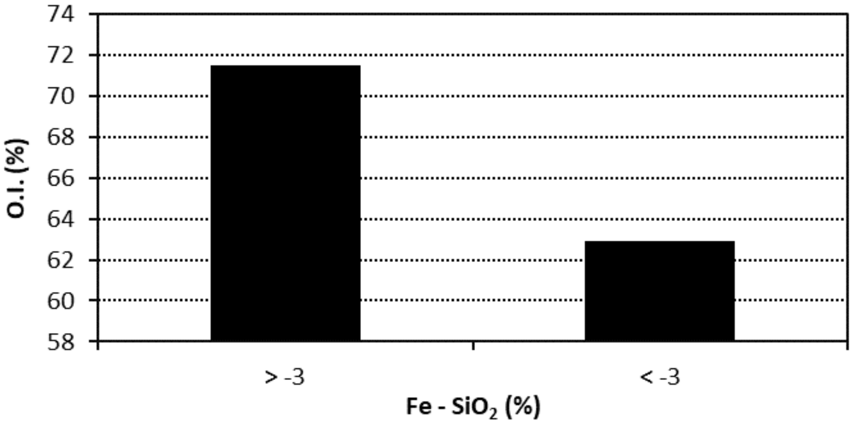

Fig. 7. Operational Index (O.I. %) vs. the difference of iron and nickel content in the laterite ore mixture

In Table 1 that follows, laterite mixtures of both domestic and foreign ores are presented, in order to assess and explain the effect of the raw material qualitative and quantitative characteristics in the smelting reduction step operation, in terms of the viscosity of the slags produced, related with foaming phenomena, as well as the SiO_2/MgO ratio of either the ores or the slags produced, which is related with the slag melting point and the electrical energy consumption. The Greek industrial operation experience of open bath submerged arc E/Fs, including imported laterite ores utilization of C2 type (of Indonesia, Guatemala –Ore G- or Ivory Coast origin), has shown that a SiO_2/MgO ratio no lower than 3.5 and a ($Fe-SiO_2$) % content of no lower than -5% or even better no lower than -3% can be characterized as safe and economically viable. Moreover, lower SiO_2/MgO ratio increases the slag melting point in values that render the open bath operation forbidden, due to its higher melting point in comparison with the alloy's melting point and the energy consumption index even higher than 600 kWh/t of calcine, in comparison with a mean value of 450 – 460 kWh/t of calcine applied for smelting reduction of domestic ores.

Table 1. Properties of various laterite mixtures

Laterite Mixture (L.M.)	**Ni (%)**	**$Fe-SiO_2$ (%)**	**SiO_2/MgO**
L.M.1: Ore A–Ore B-Ore C (%) = 65-25-10 (%)	1.04	2.4	7.3
L.M.2: Ore A–Ore B-Ore G(%) = 45-25-30 (%)	1.17	-4.5	3.8
L.M.3: Ore A–Ore B-Ore C (%) = 50-25-25 (%)	0.96	-7.1	4.8
L.M.4: Ore A–Ore B-Ore C (%) = 45-25-30 (%)	1.22	-1.3	3.6
L.M.5: Ore A–Ore B-Ore C (%) = 45-25-30 (%)	1.25	-0.4	3.3
L.M.6: Ore A–Ore B-Ore D* -Ore G (%) = 45-15-10 -30 (%)	1.26	1.2	3.8
L.M.7: Ore A–Ore B-Ore T -Ore G (%) = 40-15-20 -25 (%)	1.26	-1.7	4.6

*Ore D: Albanian ferrous ore

Taken for granted the quite stable quality of intermediate type domestic Ore C, the quantitative characteristics of the various deposits of the limonitic type domestic ores A and B, are of vital importance for the operational stability. Moreover, participation of an intermediate type ore more than 30% in the Laterite Mixture, results in a SiO_2/MgO ratio < 3, rendering the open bath operation impossible. Apart from that, the percentage of Fe and SiO_2 content of the limonitic type ores blended in order to form the rest 70% of the L.M., is critical in order the viscosity of the produced slag to be regulated according to the (Fe – SiO_2) % relationship, so that foaming phenomena are controllable and do not result in high height of slag insight the furnace and low E/F power operation, for safety management issues.

L.M. 1 of Table 1 can be characterized as a Baseline scenario for the Greek nickel industry, since it constitutes a typical example that corresponds to a stable operation. On the contrary, L.M. 3 can be characterized as a Slag High Viscosity scenario (SHV), and it constitutes a typical example of ore blending corresponding to an unstable operation in Greek Fe-Ni industry. More particularly, Ore B was up to 2014 the regulatory factor of the L.M formation, taken for granted that its higher Fe content rendered its participation of not higher than 25% enough in order to assure satisfactory viscosity of the produced slag. At the same time, due to its lower Ni content compared to ore A, its participation at higher than 25% values was not possible due to the decrease of the total Ni content in the feed. The Baseline scenario (year 2012), resulted in the production of an industrial slag (FeO = 40.57%, SiO_2 = 36.73%) with a viscosity of 72.5 poise, based on the Urbain Model. On the contrary, LME nickel price crisis after 2015, resulted in drastic cuts in mining costs, something that predominantly altered the chemical character of the Ores A and B fed in the metallurgical plant, as depicted in Figure 8. Difficulties in supply of the plant with the required quantities of Ores A and B, as well as the very low Ni (%) content of Ore B (<0.85%), resulted in the mandatory increase of Ore C participation, with L.M 3 (High Slag Viscosity scenario, December 2019) a typical example of such a case. The production of an industrial slag (FeO = 31.9%, SiO_2 = 43.81%) with a viscosity of 138.0 poise, caused serious increase in the energy consumption index MWh/t Ni, due to the decrease of the O.I.

L.M.2, is a typical example of blending domestic limonitic type ores with intermediate type laterite ore of Guatemala origin (Ore G, Ni% = 1.79 on a dry basis). Even within the period of crisis (August 2019), where the Ni content of Ores A and B were considered as low (0.95 and 0.78%, respectively), the total Ni content of the mixture was significantly increased (1.17 %). Additionally, the period of time of almost a month that high Ni grade ore participated in the L.M., the operation was generally stable, with no serious slag foaming phenomena, low energy consumption indexes and high recovery rate, indicating that this should always be the strategic operational plan for the Greek Fe-Ni industry. Moreover, the specific energy consumption indexes (MWh/ t Ni, GJ/ t Fe-Ni) were reduced by almost 10%, which is indicative of the importance of the use of such a feed apart from the economic viability of the process, also for its environmental footprint, as it has been investigated in LCA analysis concerning the ferronickel industry in literature [7,8].

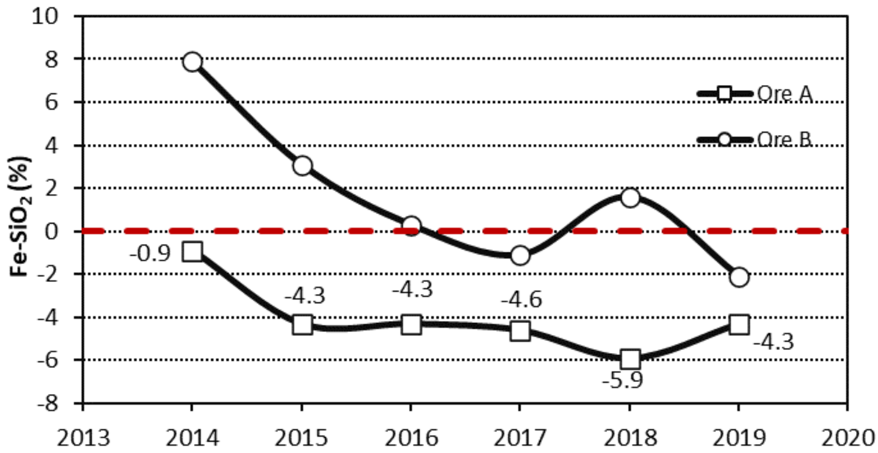

Fig. 8. (Fe – SiO_2) % values of ores A&B vs. time

Based on the study of the database of various proven deposits of the Greek Mines in Evia island and Ag. Ioannis, theoretical laterite mixtures were created, only with participation of domestic deposits (L.M. 4 & 5), as well as with the participation of imported ores: Ore G, Turkish ore (Ore T, limonitic type) and Albanian ore (Ore D, Ni (%) = 0.97, Fe = 35.3%, SiO_2 = 21.0%) [9], which is a high iron limonitic type ore able to replace Ore B in a considerable extent. In all the aforementioned cases, which can be characterized as the Optimal Scenario (OS), the goal is as seen in Table 1, the indexes for obtaining the optimal laterite's feed management Fe-SiO_2 (%) and SiO_2/MgO not to be lower than the critical values -5 and 3, respectively. Moreover, the highest possible Ni grade obtained in such a way is approximately 19% higher (1.26-1.3%) compared to a typical annual average of the period 2011-2014 (1.04 – 1.06%).

Typical phase diagrams were created via the equilibrium module in FactSage7.0 professional software, mainly to determine the melting points of typical industrial slags produced by Laterite Mixtures similar with those of Table 1. It is noted that the effect of the refractory Cr-bearing spinel mineral phases has not been taken into consideration for the calculation of the melting points. The temperature determined each time as 'melting point' was the liquidus temperature, at which all the mineral phases of the industrial slags are melted, apart from the Cr-bearing solid spinel minerals that still co-exist, even at 1.600 ºC. In case of the phase diagrams of slags produced by partial substitution (30%, SiO_2/MgO = 4.18) or total substitution (100%, SiO_2/MgO = 2.1) of intermediate type foreign laterite (Ore G) in the L.M., the mineral phases orthopyroxene, clinopyroxene $(Mg,Fe)_2Si_2O_6$ and olivine $(Mg,Fe)_2SiO_4$ co-exist in equilibrium with liquid slag at significantly higher temperatures and at higher contents. Moreover, when the SiO_2/MgO ratio is decreased at levels lower than 3, the melting point of the slag was increased up to 1,432 ºC, in comparison with 1,220 ºC, as seen in Figure 9. In Figure 10, the melting points of typical industrial slags, defined as solidus temperatures, are depicted by the use of FactSage7.0 software and the Phase Diagram module in a ternary system FeO – MgO – SiO_2.

In the plotted area DS (Domestic Laterites) melting points of typical industrial slags are depicted (FL_A and FL_B, solidus temperature 1,256 ºC, with SiO_2/MgO 5 and 7, respectively), produced by different blend ratios of domestic laterite ores. Moreover, the melting point with the code name TS (Tropical Scenario) is also depicted (solidus temperature 1,380 ºC, with S/M 2), which corresponds to the slag produced by a 100% foreign (Ore G) tropical origin ore feed. It is verified the trend that the low Fe content and the high MgO and SiO_2 content of ferronickel slags produced by the total participation of intermediate type laterite ores (like Ore G) in the L.M., results in an increase of the slag melting temperature by almost 200 ºC. A critical parameter for this is the remarkable presence of the olivine mineral phase in such a case, and especially forsterite (Mg_2SiO_4). On the contrary, the remarkable presence of the Fe – bearing spinel mineral phases (such as $MgFe_2O_4$) and magnesiowustite (Mg,Fe)O is a critical parameter for the low-melting point ferronickel slags produced by domestic laterite ores.

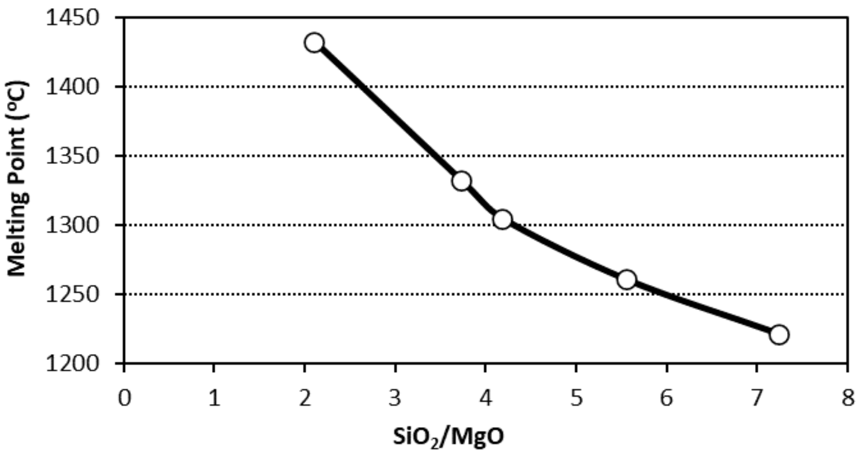

Fig. 9. Melting point of industrial slags v/s SiO_2/MgO ratio

In Figure 11, the correlation between the basicity of the same industrial slags and their viscosity calculated by the Urbain model is depicted. Moreover, increase of the viscosity of a low basicity slag in higher levels than 110 poise, close to that of the slag produced by the L.M 3 fed in the R/K-E/F system, with a Fe-SiO_2 (%) ratio lower than -7, corresponds to intensive foaming phenomena, low operational index and high energy consumption.

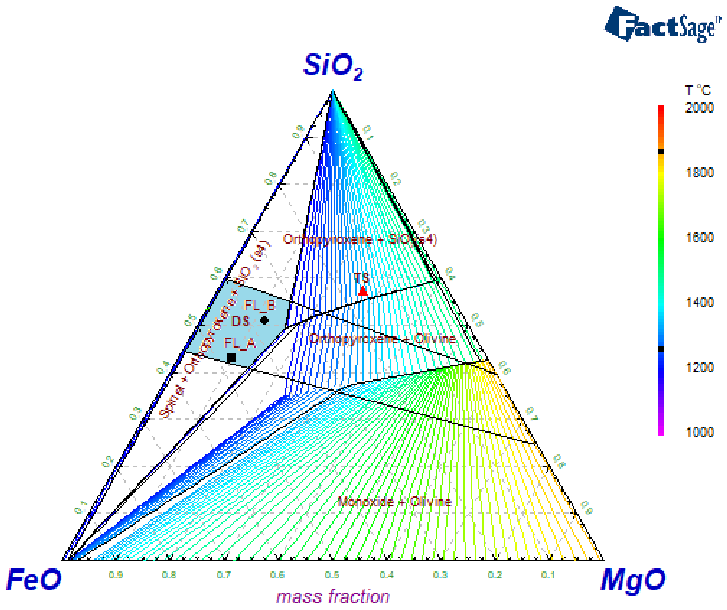

Fig. 10. Melting point of laterite slags in a ternary system FeO – MgO – SiO_2

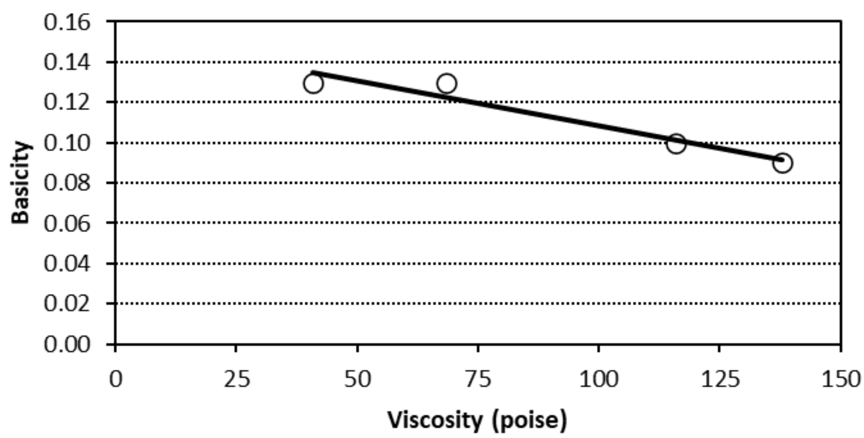

Fig. 11. Basicity vs viscosity of industrial slags

Within this framework, making the assumption of the linear fitting of the historical Ni (%) – O.I. (%) and MWh/t Ni data from the Greek industrial operation database, a quite conservative prediction for obtaining an energy consumption index of 58 – 59 MWh/t Ni could be made. Taking as bases of the consideration: i) the upper limit of processing no more than 2,350,000 t of calcine annually by the R/K – E/F system and ii) the cost of the electrical energy is approximately 30% of the total cost of the nickel extraction, assuming that the energy prices will at least come back to the level before 2022 (70 €/MWh), an annual Ni production of 7.000 t is regarded as absolutely realistic for operation of two E/Fs, just for a potential beginning of the reoperation period of the Greek Fe-Ni industry. In such a case, a selling price of 15,000 €/t of Ni, could be very close to the marginal cost of the industry.

In any case, the conclusion that can be clearly drawn is that increase of the FeO content of the E/F slag, which is intimately related with the Fe content of the Laterite Mixture, as well as increase of the slag basicity, also intimately related with the decrease of SiO_2 (%) content, results in considerable decrease of intensive slag foaming phenomena [10,11] and a series of operational problems. This can be clearly seen in Figure 12, where the evolution of ratio of energy consumed/energy loss due to operational problems caused by the poor quality of the laterite feed (Ni grade, Fe – SiO_2), is presented. The aforementioned ratio in 2019, a year which was the worst concerning the quality of the laterite feed, fell from 8.7 in 2011 to 5.6, with the respective negative results in Ni production of the plant. The loss of income due to the energy losses due to operational problems caused by the poor laterite ore quality, was almost 22 M€ in 2019. The extent of the serious operational problems that the Greek Fe-Ni industry faced, affecting both the collapse of the E/F O.I. and the safety of personnel and equipment, due to the poor laterite feed quality (mainly regarding the quite negative Fe – SiO_2 relationship) during the period 2015-2019, is concisely presented by means of *case studies*.

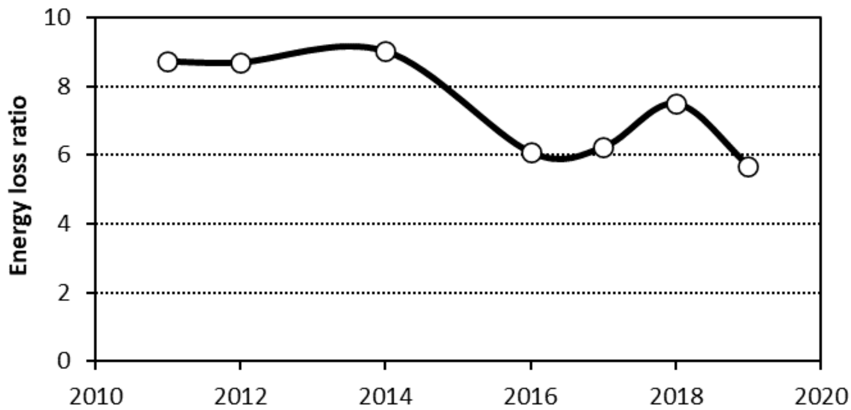

Fig. 12. Evolution of the energy loss ratio (energy consumed/energy loss due to operational problems caused by the poor quality of the laterite feed) in the period 2011-2019.

Uncontrolled E/F operational case studies. A typical case study of an extremely dangerous and unstable E/F operation, due to very bad quality of laterite feed, is that of 2017. Based on operational data, the Fe-SiO_2 (%) content of limonitic type Ores A and B was -6 and -3, respectively, resulting in a two-days operation of the E/F which demands the difficult management of intensive slag foaming phenomena, current fluctuations, power loss due to intensive electrode consumption, very high flames around the freeboard surface, very high slag viscosity that renders slag tapping very difficult and inability of maintaining calcine side-wall protection, because of the high slag level inside the E/F. The aforementioned serious operational problems, resulted in an uncontrolled metal tapping from the E/F side-wall shell the second day, which caused in addition to the other big decrease of the plant O.I., as well as increased cost of maintenance. In Figure 13, a typical picture from the E/F PLC operation is presented.

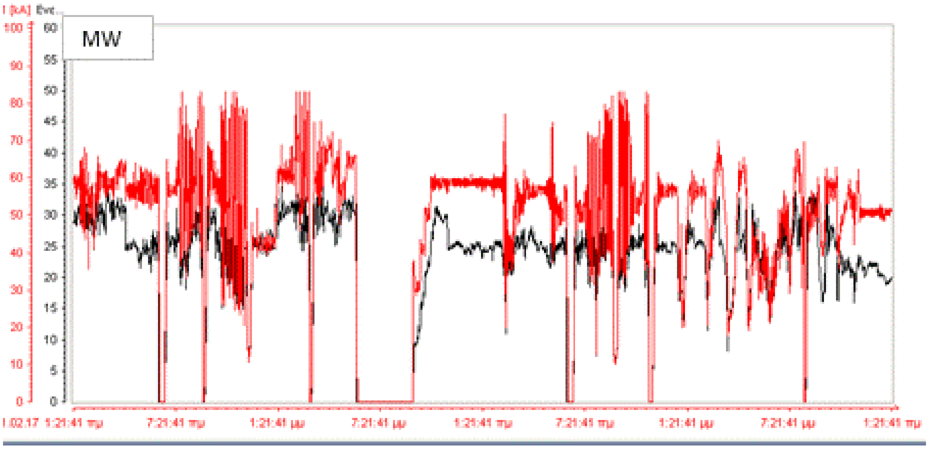

Fig. 13. PLC data of E/F unstable operation due to low quality laterite feed

3.2 Solid Fuels

The stable quality of the solid fuels used for roasting reduction in the Greek Fe-Ni industry plays a very important role in the final result of the smelting reduction step [12]. More precisely, either the combination of three solid fuel types (lignite, coal and coke) or two types (coal and coke), depending on the international fuel prices, should assure the retention of the needed temperature profile in the R/Ks, in order a calcine of the highest possible temperature to be fed in the E/Fs. In such a way, electric energy consumption is decreased and the operational problems in the smelting step due to slag foaming and intensive reduction phenomena, are minimized. A prerequisite for the aforementioned is a solid fuel mixture fed in the R/Ks with the optimum ratio of volatiles and fixed carbon (C^{fix}).

During 2010, there were periods of time when for cash management reasons, it was selected not the stable long-term co-operation with coal suppliers, who have the proved ability for supplying a certain quality of coal adjusted to the needs of the Greek Fe-Ni industry. Instead of this, it was selected the supply of spot ship loads of two different types: 'hard coal', with volatile content <25% and 'soft coal', with volatile content >35%, in order to be mixed in ratios that would lead to the achievement of the stable temperature profile inside the R/Ks. Nevertheless, it was proved by the industrial experience that especially the lack of lignite feed in such case, causes the inability to manage the optimum volatile combustion along the R/Ks, causing extremely dangerous operational situations for the E/Fs. The most typical case study was that of an E/F in 2010, that after almost a month fed with calcine of very low temperature with excessive content of C^{fix}, its O.I. was dramatically decreased to lower than 59% on a three – month basis (almost 30% lower than the annual average). Moreover, intensive slag foaming and reduction phenomena finally led to such an uncontrolled slag height inside the E/F, that all the freeboard was covered by slag.

Solid fuels' granulometry also was proved by the industrial experience that is critical for the result of the smelting reduction step. As seen in Figure 14 at periods of utilization in the R/Ks of spot ship loads of coal with -1 mm (%) grain size higher than 25%, instead of 16-20% when the best operational results were achieved, the E/F recovery rate was significantly decreased by almost 12%. This can be attributed to the fact that more fine grained coal in the R/Ks, due to its easier combustion, cause a higher than required exit temperature of the calcine fed in the E/Fs. The former results in significantly higher Ni% grade in the E/F alloy phase (>14% on average), which is intimately related with lower recovery rates.

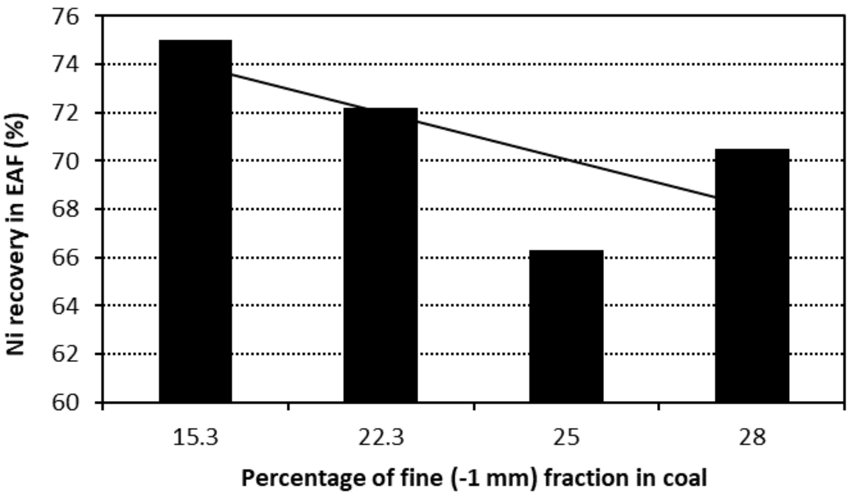

Fig. 14. Nickel recovery rate (R%) in E/Fs vs the percentage of fine (-1 mm) fraction in coal

3.3 Maintenance

Within the nickel price crisis period 2015-2020, tremendous cuts in the maintenance expenses program took place as well, being respectively critical for the disappointing result of the industrial operation. Nonetheless, apart from the objective problem of funding the Greek Fe-Ni industry the period 2015-2019, there should be a shift from the philosophy of corrective maintenance to the preventive maintenance one, being incorporated into a holistic maintenance management system [13]. Moreover, the lack of replacement of very low-cost spare parts, either due to lack of funding or within the framework of just corrective and no preventive management strategy, resulted in great production loss as well as dangerous operational situations.

Further emphasizing on such a typical case study, non - replacement of flexible conduits of E/F transformer within the framework of the shutdown of the furnace few months before for the annual general maintenance, resulted in the non – uniform conduction of the electrical current to each of the EAF conduct clamps. Thus, permanent overheating of a certain contact clamp resulted in the wear of the clamp, water leakage inside the E/F, danger for the safety of personnel and equipment, melting of steel behind the clamp (Figure 15) and removal of the electrode baking zone considerably higher. Additionally, there was an income loss of 3M€ and a 30 days shutdown of the E/F, due to the lack of spare parts with a cost of just 5,000 €.

Fig. 15. Case study of melted casing steel due to overheating

3.4 Human resources and Knowledge operationalization

Despite the fact that the Greek Fe-Ni industry operates for over 70 years, mainly due to structural malfunctions, it is true that there is an absolute need for the application of a new management strategy concerning human resources management and process formalization - standardization. Experience can be characterized as a very essential knowledge asset for a metallurgical company, which therefore is quite difficult to be quantified [14]. Moreover, a sustainable and techno-economically optimal operation is difficult to be obtained, without a combination of applying a knowledge management system with the standarization of policies and procedures [15]. Thus, within the framework of planning to restructure the administrative philosophy of a privatized company in the future, it is quite essential to emphasize on the following parameters:

- **Culture of sharing responsibility for collecting and transferring the important knowledge**: loss of experience results in productivity decrease and lack of a sustainable competitive advantage of the Greek Fe-Ni industry. Within this framework, incentives should be given to skilled and experienced workers to remain to the metallurgy and assure successful troubleshooting in difficult -to -handle situations.
- **Tacit knowledge transfer** through organizing internal learning events, enhancing innovation through rewarding out of the box imaginative efforts, or conducting regular internal knowledge exchange forums.
- **Establishment of standarization procedures** for every single metallurgical process, including troubleshooting procedures, instructions with certain guidelines enriched with policies at which all the personnel should adhere. There were many

cases were the lack of clearly described step-by-step procedures resulted in lost unit operation time, with respecting loss of thousands of Euros.
- **Introduction of modern IT systems**, for thorough cost monitoring management.
- **Implementation of best practices and best available techniques on health and safety training**, including safety seminars and establishment of modern on-the-job-training techniques.

4 Conclusions

The perspective of re-operation of the Greek nickel industry is a big challenge not only for the raw materials sector but also for the export character of our national economy, in general. Assessment of the big database of Greek nickel industry's operational data of the E/Fs from a techno-economic point of view, constitutes a useful tool for the required management planning, concerning the enterprise operation under a new ownership structure. It is clearly deduced by the current work that it is absolutely critical for achieving the optimum and cost-effective productive result of the pyrometallurgical process, the application of a strategic plan emphasizing on the following:

- **Assurance of the supply of the plant with high Ni grade (Ni%> 1.8 % on a dry basis)** imported laterite ores, with a participation of 35-40% to the laterite mixture and at the same time supply with domestic limonitic type laterite ores with the highest Ni (%) content and Fe (%) and SiO_2 (%) content fluctuating among certain marginal values. The aforementioned, in combination with the stable quality of critical raw materials, such as solid fuels and electrode paste, are the prerequisite for obtaining an Operational Index 75% at least and a special energy consumption lower than 60 MWh/Tn Ni. Therefore, an updated detailed study of the proven domestic ore reserves is very important to confirm that a laterite feed with approximately 1.26 % Ni content on a dry basis, is possible to be practically obtained.
- **SiO_2/MgO percentage ratio higher than 3 and difference of Fe-SiO_2 content higher than -5%**, constitute one of the basic pillars for assuring a stable and safe operation in open bath E/Fs.
- A strategic administrative decision for long-term contracts with suppliers of solid fuels (coke, coal and lignite in addition to the domestic sources of lignite if needed), is a parameter that significantly enhances operational stability and safety in the E/Fs. Industrial experience has shown that occasional co-operations with suppliers in order to face cash flow problems, accompanied by feeding of R/Ks with either fine-grained coal or different qualities of coal with less than the required volatile content, especially in the absence of lignite as a regulatory agent, result in a big decrease of Operational Index in E/Fs, even 30% lower than the expected and significantly lower recovery rates (>10% decrease)
- **Introduction of a holistic maintenance management system with the introduction of modern IT tools for cost analysis**, as well as the shift from the philosophy of corrective maintenance to preventive maintenance, is very essential, increase decisively the E/Fs Operational Index.

- **There is a need for application of modern HR management tools and techniques**, such as tacit and explicit knowledge transfer management strategy, incorporated in a holistic total quality long – term management plan.

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