

THE STATE OF THE ART IN NICKEL SMELTING: DIRECT OUTOKUMPU NICKEL TECHNOLOGY

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Abstract

In 1959 Outokumpu started up an integrated nickel smelter and refinery at Harjavalta. The flash smelting – Peirce-Smith converting route was applied, and the high-grade converter matte was further refined to nickel cathodes by leaching and electrowinning. In 1995 the production capacity was increased from 17 000 mtpa to 52 000 mtpa, based on the **Direct Outokumpu Nickel Smelting Process**. The additional refinery capacity is based on hydrogen pressure reduction, producing nickel powder and briquettes. The smelting operation is currently part of Boliden Group and the nickel refinery part of OM Group.

In the DON technology, high-grade nickel matte with low iron content is produced in the flash smelting furnace directly without subsequent converting. The metal values in the smelting slag are recovered in an electric furnace as an iron containing Ni-matte. The mattes produced differ from the conventional nickel mattes in many respects, and therefore focused R&D efforts have been made in order to cope with their melting points, fluidities and settling properties.

When developing and operating metallurgical processes it is crucial to manage and control the characteristics of the products as well as by-products generated in different steps of the process chain. The low melting points of the high-grade nickel mattes produced in the DON furnace, particularly those low in copper, have pointed out challenges in the furnace design, in particular in the hearth and its thermal engineering. Also key issues of the DON technology are smelting of high-magnesia concentrates, the recoveries of nickel and copper, as well as those of PGM's and cobalt. These factors can be affected by a proper selection of the process concept, and the operational conditions in the processing vessels.

This paper deals with the experience of the DON technology gained over the first ten years of operation, including the significant environmental impacts. Selected results of the thermodynamic modelling of DON and EF mattes and high-magnesia slags are reviewed, with the reference to the mattes produced. Also the design principles of the FSF and EF will be discussed.

Introduction

During recent years there has been a lot of discussion on new leaching technologies replacing pyrometallurgical routes. However, about 90% of the world's nickel production capacity is still based on pyrometallurgical processes. It is also important to note that there are six operating nickel flash smelters based on Outokumpu technologies making more than 50% of nickel matte smelting production capacity. Refining of high-grade nickel matte utilizes mainly hydro-metallurgical methods. Also in that area Outokumpu has extensive technological experience.

Nickel Raw Materials, Production, Consumption and Trends

The importance of nickel comes from its ability, when alloyed with other elements, to increase a metal's strength, toughness and corrosion resistance over a large temperature range. Nickel is essential to the iron and steel industry, in particular to stainless steel and nickel-containing alloys play a key role in numerous aerospace, marine, electronics and construction applications [2].

NICKEL PRODUCTION AND CONSUMPTION 2003-2009

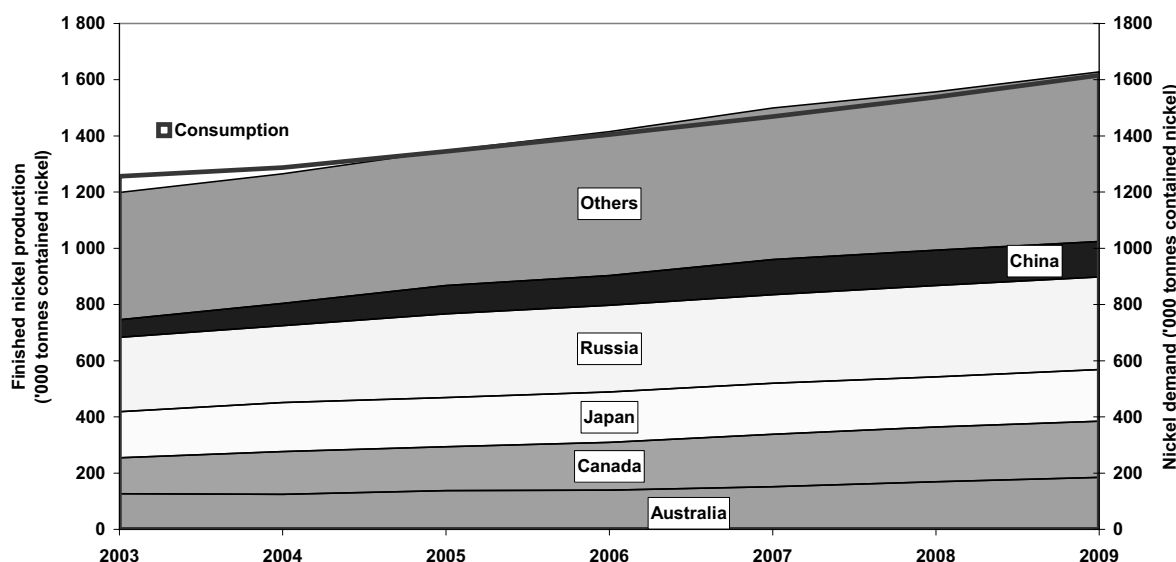


Figure 1. Forecasted nickel production and demand ('000 tonnes contained Ni) [1].

Raw Materials

Nickel in the earth is found in two different types of liberalizations: sulfidic and lateritic. The laterites can be further divided into two types: limonites (<5% MgO and < 1.5%Ni) and saprolites (MgO up to 35%, Ni 2-3%) [3]. Besides with nickel, the sulfidic ores contain copper, cobalt, and Platinum Group Metals (PGM's) in considerable amounts, which play economically more important role compared to nickel. Impurity contents such as arsenic and magnesia may cause problems in the processing. The variety of raw materials and products results in tailored needs for the process technology with a specific type of raw material.

Production and Consumption

70 % of the world mine production in 2003 was provided by five countries: Russia, Australia, Canada, Indonesia and New Caledonia. The distribution of nickel refinery production is little bit more diverse, the major producing countries, Russia, Australia and Canada, being still the same. Japan, although possessing high demand, does not have natural resources.

By the end of year 2004 industry stocks of nickel have been record low and LME nickel prices were trading well above long-run average levels. However, in medium term there appears to be many nickel projects, and some possibility for oversupply in the years 2007-2009, see Figure 1. The world consumption of nickel is currently more than 1.2 M mtpy, whereas the production broadly speaking is in balance this year.

Nickel products are divided into three groups [2]: refined nickel (class I) 99% or more: electrolytic nickel, pellets, briquettes, granules, rondelles and powders/flakes, charge nickel; (class II) < 99%: ferronickel, nickel oxide sinter and utility nickel, and chemicals (class III).

Trends

Looking forward, world primary nickel production is expected to increase by more than 5 % per year [3]. High prices have intensified exploration activity and thus new potential nickel projects around the world. The largest green field projects published include Voisey's Bay, Ravensthorpe and Goro.

Although there has been much discussion concerning pressure acid leaching replacing the smelting technology, at the time being, only 10% of nickel production capacity is processed by leaching methods [4]. Furthermore, even in the years to come pyrometallurgical technologies are expected to dominate the production as a first processing step by more than 80 %.

Pyrometallurgical treatment of a sulfidic concentrate commonly includes roasting, smelting and converting. In the flash smelting, roasting and smelting are combined. Matte from the converting is further processed by hydrometallurgical methods. Today, Outokumpu Flash Smelting together with Direct Outokumpu Nickel (DON) technology have become the prevailing methods for nickel smelting, as illustrated in Figure 2.

Today there are six Outokumpu-type nickel flash smelters operating in the world, accounting for over 50 % of the existing smelter capacity. The original concept was in operation in Harjavalta, and it is still applied today in two smelters, Selebi-Phikwe in Botswana and Norilsk in Russia. The Harjavalta smelter was modified in 1995 with the novel DON technology. The newest nickel flash smelter started operation in 1998 in Fortaleza Brazil, also based on the DON concept. The Kalgoorlie (Australia) and Jinchuan (PR China) smelters use the Outokumpu flash smelting furnace, where the smelting and slag cleaning stages have been built together to form one integrated smelting and slag cleaning unit.

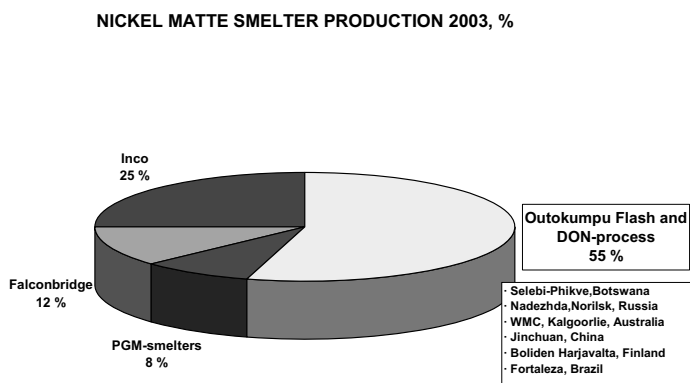


Figure 2. Nickel matte smelter production capacity in the world.

Outokumpu refinery technology with parallel leaching circuits for the flash furnace matte and the electric furnace matte is used in Harjavalta. Outokumpu refinery technology has been applied also for nickel carbonate raw material. The original leach-purification-electrowinning technology or parts of it have been supplied to other producers.

Harjavalta Ni-operation

An incentive for Outokumpu's nickel production, started in 1959 at Harjavalta, Finland, was the discovery of the sulfide nickel ore body at Kotalahti. Although other options were available, it was natural that also for nickel concentrates the flash smelting method, adopted for making

copper at Harjavalta in 1949, was applied. In 2003 New Boliden was incorporated and from the beginning of 2004 Harjavalta smelter has been part of that company.

Smelter Developments

The original smelter flow sheet consisted of three main process steps: flash smelting, Peirce-Smith converting and electric furnace slag cleaning. The initial design capacity of the plant was 3 000 mtpa metallic nickel. Over the past decades, several modifications have taken place and the capacity has been increased. The expansions were in 1972 and 1982, followed by a major renovation in 1991.

The latest expansion of the plant was completed in 1995. This project primarily aimed at a higher cost efficiency, but the environmental issues were also important. Besides the capacity increase up to 40 000 mtpa Ni, the entire process chain was fully modified. The smelter flow sheet was simplified by the newly developed DON-technology [5,6]. Its major feature is the elimination of the converting step. Instead of the high grade converter matte the smelter now produces two types of mattes: the flash furnace (FSF) matte and electric furnace (EF) matte [7].

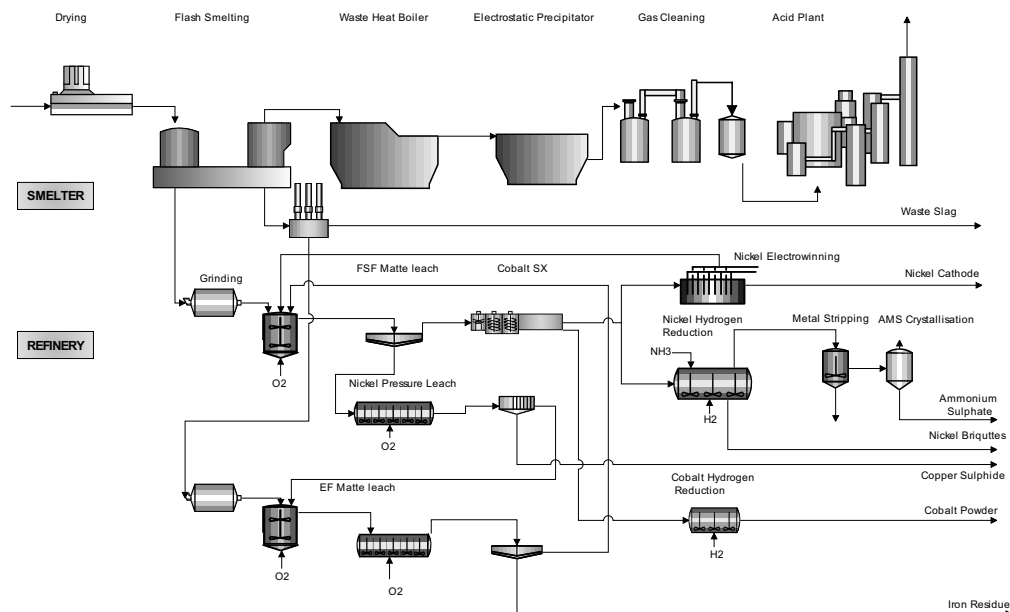


Figure 3. Harjavalta nickel smelter and refinery flowsheet.

The Smelter Flowsheet Today

In the DON technology as implemented at Harjavalta, dried concentrate is flash smelted in one step directly to a high-nickel low-iron matte [8]. The FSF slag is laundered to the electric slag cleaning furnace, where nickel is recovered as a metallised matte containing iron. Melting temperature of the EF matte is adjusted by injecting nickel concentrate through a lance into the melt because of the low sulfur content of incoming slag, for sulfur content of the matte in order to adjust its melting temperature. The FSF and EF matte is granulated by water quenching of sprinkled melt. After grinding they are fed to the new hydrometallurgical processes for refining [7]. The overall flowsheet of the whole operation is presented in Figure 3.

Year 2000 OM Group Inc. took over the nickel refinery operation. The refinery has since that gone through some modification by OMG, but the refinery's main process operates principally on the same basis [4].

Features of Outokumpu's Nickel Smelting Technologies

The original nickel flash smelter-refinery concept by Outokumpu may be satisfactory in many cases, fulfilling the basic economic and environmental requirements of today [9-10]. In a competitive environment, however, pressures to improve the plant performance will become ever stronger. Therefore, it is important for us to continuously look for new solutions and options to make smelting and refining technologies still more effective. In the following chapters, the DON smelting options and their development will be discussed.

Raw Material Flexibility

Nickel content in sulfidic nickel concentrates typically ranges from 5 to 12 % Ni. Concentrates from Western Australia have higher nickel concentrations typically 20 % and even up to 25 % Ni. Copper contents in these concentrates are very low, even below 0.1 % Cu, while in other concentrates they are relatively high, 1 - 6 % Cu. This feature enhances the operational point of the smelter using various raw materials, including nickel-bearing metallic and non-metallic secondaries.

An essential constituent in nickel concentrates often is cobalt, which is more valuable than nickel. Concentrations of cobalt vary in the range of 0.2 - 1 %. A high recovery of cobalt is thus of great importance to the profitability of a smelter. Analyses of some nickel concentrates used, tested and studied successfully by Outokumpu for the DON technology are shown Table I, ranging from low-copper raw materials to concentrates with Cu/Ni > 1 as well as from MgO-lean feed mixtures to those with Fe/MgO \approx 3.4. This indicates the superior capability of the processing technology to digest a wide range of raw materials.

Table I. Nickel Concentrate Analyses Used or Tested for the DON Smelting

Concentrate	Ni %	Cu %	Fe %	Co %	S %	SiO ₂ %	MgO %	Ni/Cu	Fe/MgO	Fe/SiO ₂	PGM g/t	Ag g/t
Case A ²	6.0	13.3	39.6	0.23	32.0	2.9	1.2	0.4	33.0	13.9		
Case B ²	15.0	2.0	45.0	0.7	36.0	<0.5	<0.5	7.5	>90	>90		
Fortaleza ^{1,3}	6.8	1.3	37.5	0.14	23.0	17.1	7.3	5.4	5.2	2.2	2.2	3.1
Case C ²	13.9-14.7	0.2-0.4	28.5-31.9	0.31-0.39	28.5-29.5	6.8-7.4	7.4-8.3	34-87	3.4-4.1	4.1-4.3		
Harjavalta ^{1,3}	11.5	1.5	24.5	0.36	21.8	23.2	5.3	7.9	4.6	1.1		
Case D ²	9.6	4.6	35.9	0.46	28.6	9.2	7.1	2.1	5.1	3.9	14.8	13.0
Case E ²	6.9	3.3	35.8	0.17	26.0	9.3	7.5	2.1	4.8	3.8		

¹feed mixture

²feasibility study

³operating plant

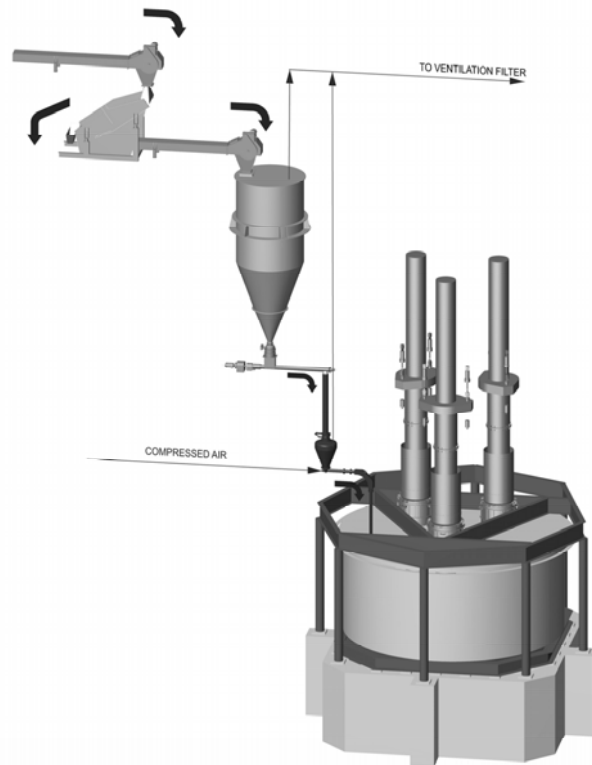
Equipment and Process Development

The DON technology allows optimization of the smelting and refining process conditions according to the requirements of raw materials and the products, as well as other boundary conditions [10]. Conditions of the slag cleaning step can be adjusted independently from the flash smelting. In the EF area in addition to the industrial scale plant trials, an extensive CFD study has been conducted on the fluid flows and metal droplet settling [11-12] in order to ensure sufficient metal value recoveries. For example in Fortaleza, where nickel content of the concentrate is relatively low, the oxidation is milder than in Harjavalta and the FSF matte contains more iron. Also for the sulfidation of EF matte several methods are available. Harjavalta utilizes concentrate injection carried out batch-wise using a consumable steel lance immersed in the slag layer,

Figure 4, while in Fortaleza liquid flash smelting matte is used. Concentrate injection has proved efficient and reliable for modification of the EF-matte composition.

Figure 4. Concentrate injection stage used for sulfidising the EF matte prior to tapping and granulation.

The DON process can be operated also with a full EF matte circulation to the flash furnace. Thus, only a low iron FSF matte is produced which simplifies the refinery flow sheet [4] as a result of decreased iron removal. This concept provides, however, that the feed materials do not contain such elements in significant concentrations that would accumulate in the circulation between the furnaces, e.g. cobalt. On the other hand, the concentrates containing PGM's may benefit from this concept. Matte circulation has been successfully tested on a pilot scale. In addition, industrial tests have been carried out at Fortaleza. Today, Fortaleza smelter applies a partial matte circulation.



In addition to the original DON technology [6], Outokumpu has developed a new process concept, where instead of concentrate, solidified nickel matte is used as a feed material to a flash smelting furnace. This procedure called continuous nickel converting is applicable, for example, to old plants where the existing electric furnaces can be used to upgrade the feed material suitable for flash smelting. By this concept, the batch-wise blowing PS converters can be replaced by a single flash smelting furnace.

The main function of the concentrate burner is to mix properly the solid feed and process gas. The good combustion of the feed mixture is ensured by accurate and simultaneous feed mixture and process air speed controls, enabled by the state of the art concentrate burner. The Outokumpu Sleeve Type Burner, see Figure 5, may be combined with accurate feeding and solids transport devices, such as Outokumpu Loss-in-Weight feeder and the Air Slide [13]. They are results of extensive research and a long-term operational experience.

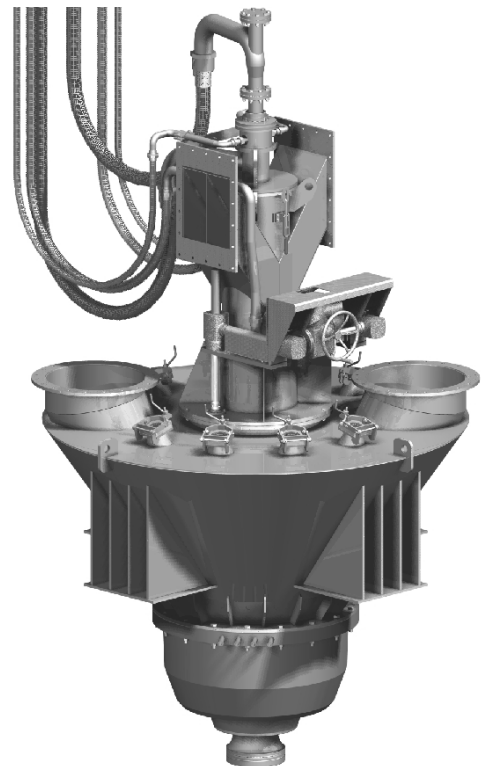


Figure 5. Current design of the Outokumpu concentrate burner with adjustable process air velocity, auxiliary oil lance and optional air slide for feed mixture transport.

Recoveries of Precious Metals and Cobalt

The nickel and copper recoveries in the conventional Flash Smelting - PS route are typically high, despite its extensive material circulation. On the other hand, the cobalt recovery is relatively low. As no converters are used in the DON technology, the material circulations between the process units are minimized, with a very positive impact to the cobalt recovery, see Figure 6. Also the recoveries of nickel, copper and PGM's can be maintained at a high level. While the cobalt recovery in the DON smelter has considerably improved, the significance of cobalt in the nickel refining has also been increased [4].

In the DON smelter, the PGM's are effectively collected directly into the high grade matte formed in the flash smelting furnace, and the amount of PGM's going into the slag cleaning furnace is almost nil. In the refinery copper contained in the FSF matte is converted to secondary copper sulfide carrying the PGM's effectively. The PGM-containing leach residue can be directed to the copper smelter or the sulfide can be further pressure leached to dissolve copper and to collect the metal values.

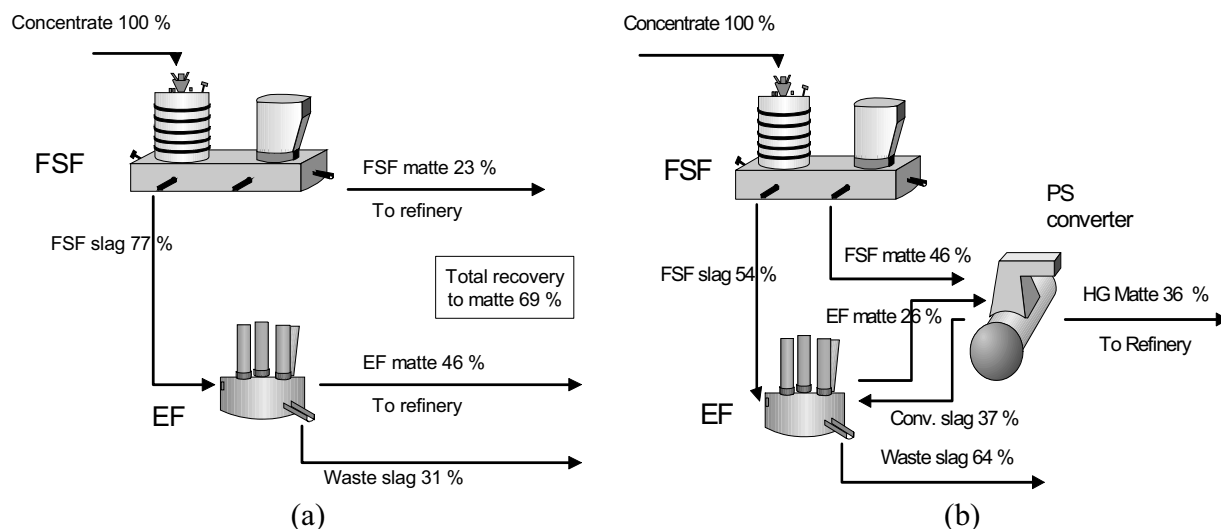


Figure 6. Cobalt distributions in the DON smelting concept (a) and in the conventional Flash Smelting - PS converting route (b) calculated from true industrial process data.

Facing the MgO Problem and Fluidity of DON-matte

As shown in Table 1, nickel concentrates may contain considerable amounts of magnesia. MgO - content of the nickel smelting slag typically varies in the range of 5 - 10 % MgO, and therefore magnesia is a basic constituent of the nickel slag systems.

Magnesia influences strongly the key physical characteristics of the slag. When its concentration in the slag increases beyond a few weight percent, the melting behavior is modified significantly resulting in higher smelting temperature and slag viscosity [14-16]. Recently, thanks to thermodynamic calculation methods and the advanced databases, a lot of new information about these kind of complex slag as well as matte systems has been generated for the development [17-18].

The operating windows of a conventional nickel FSF and the DON FSF with the same concentrate, in terms of the liquidus temperature of the slag, are presented in Figure 7. It demonstrates that with the same Fe/MgO ratio in concentrate, the smelting temperature in the DON operation may be lower than in the conventional FSF. This is due to the DON FSF oxidizing more iron from the feed mixture, thus diluting the MgO concentration and increasing the Fe/MgO ratio of the slag. Even if lime or alumina may be used for lowering the melting point, Figure 8, the DON technology does much the same without increasing operational costs due to extra fluxes [13,15].

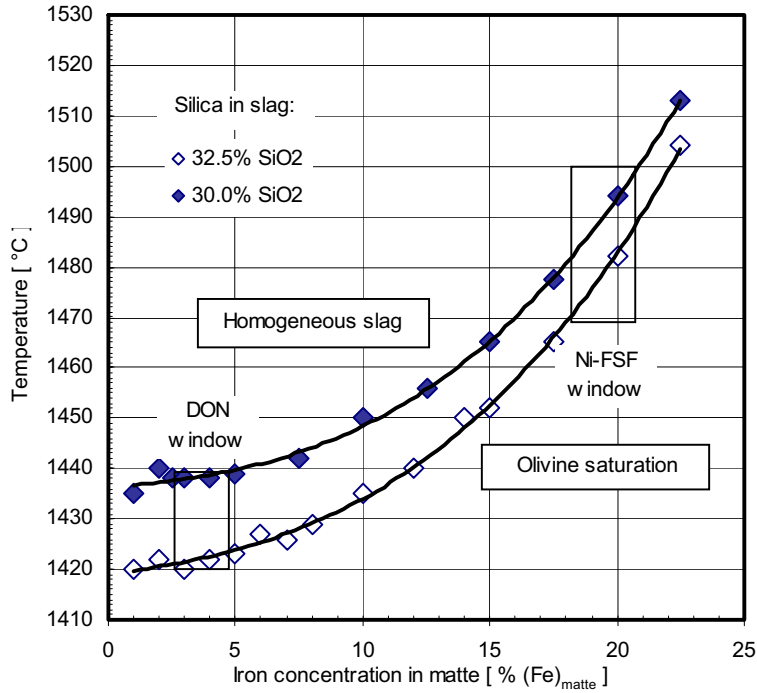


Figure 7. L liquidus temperature of the slag as a function of iron in matte in a conventional FSF vs. DON FSF; Fe:MgO -ratio of the feed mixture is 4 and Ni:Cu = 2, constant (%SiO₂).

Iron residue from the nickel refinery may be re-circulated to the flash smelting furnace [4]. The procedure has a favorable effect on the slag composition, diluting its MgO content and thus reducing the operating temperature. This also provides environmental benefit as the refinery residue is converted into an innocuous slag. In some cases, however, it may be more beneficial to discard the leaching residue as an outlet for some impurities, such as arsenic.

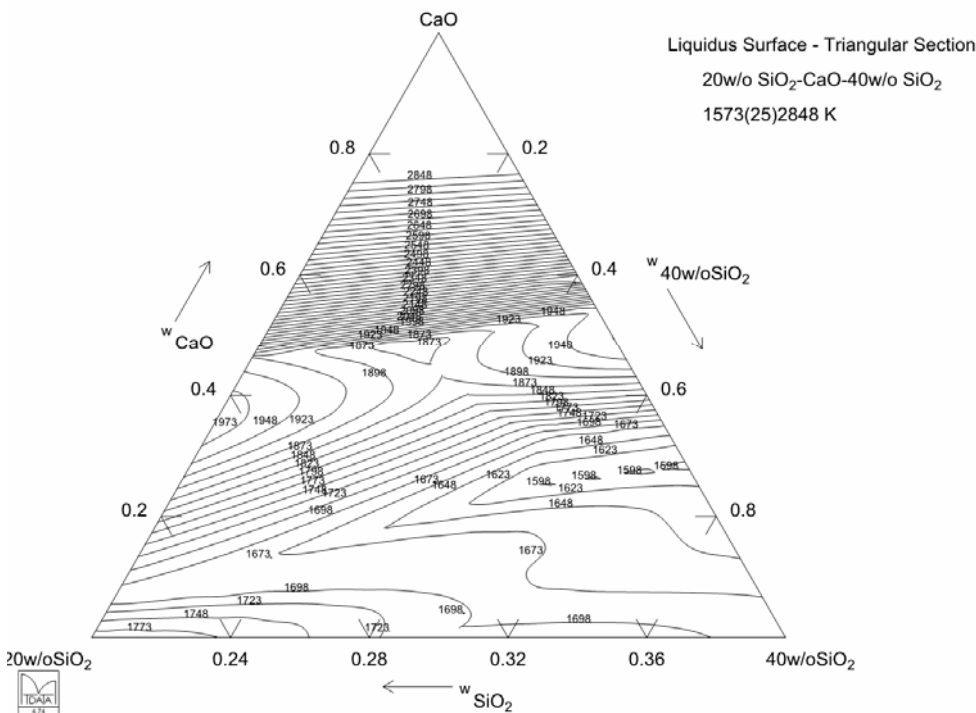


Figure 8. Liquidus isotherm diagram of a nickel smelting slag with constant Fe:MgO -ratio of 4 and 20 - 40 (%SiO₂) and the influence of CaO -modification in P_{O2} = 8·10⁻⁷ atm.

Fluidity and melting point of DON mattes, in particular at low copper concentrations, differ from copper mattes, due to the fundamental properties of the systems Cu-Fe-S-O and Cu-Fe-Ni-S-O, see Figure 9. The presence and stability of the solid copper sulfide, Cu_2S , solidifies the low-iron copper mattes at above 1100 °C, whereas metallised nickel mattes may be molten down to 600 °C or even below. Therefore, significant effort has been devoted to understanding better the fundamental properties of DON mattes, such as viscosities. This feature also puts new requirements to the FSF and EF hearth design. Therefore, new furnace and lining constructions as well as cooling system designs have been developed to ensure the furnace integrity in a similar way as in the novel direct-to-blister copper smelting furnaces [19]. The bottom air-cooling systems for FSF and EF avoid effectively matte infiltration into the refractories and their joints.

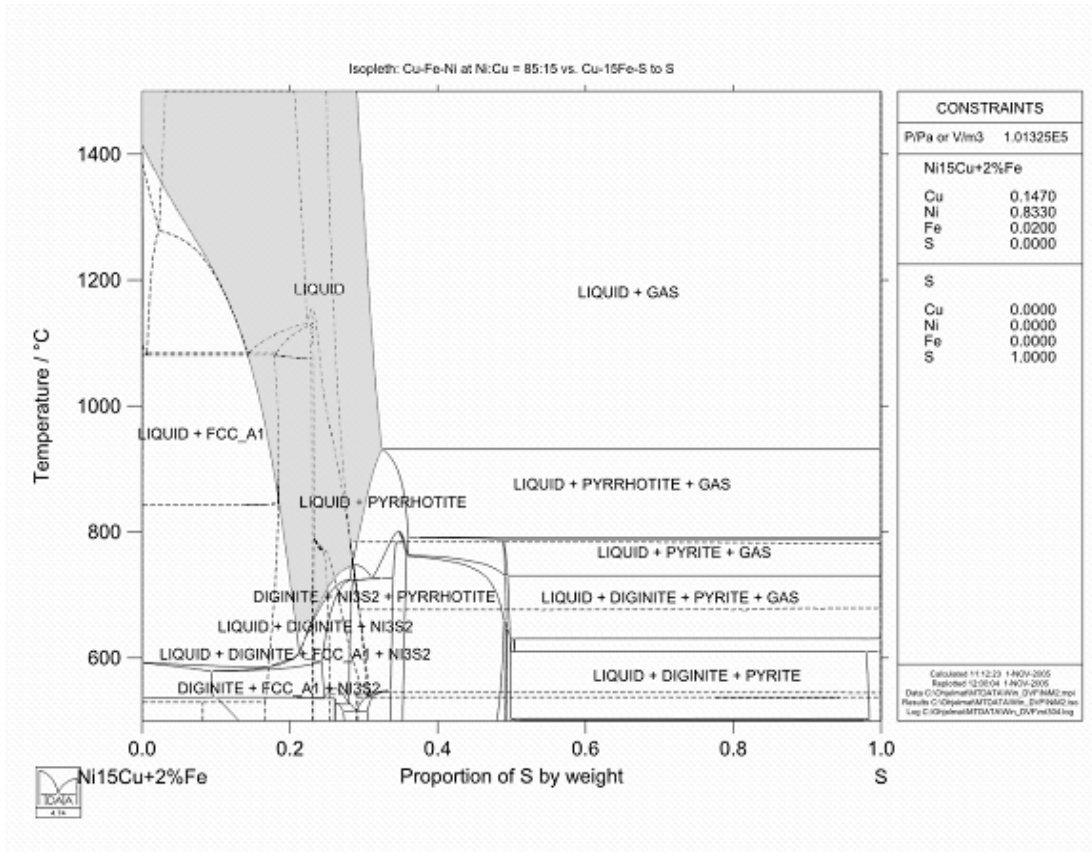


Figure 9. Calculated isopleths of a copper-iron matte (---) and a metallised DON matte (—) with Fe:(Cu+Fe+Ni) ratio 2:98 and Cu:(Cu+Ni) ratio 15:85, from metal alloy to elementary sulfur.

Investment and Operating Costs

Compared to the conventional nickel smelting, the new DON technology needs a lower number of smelting vessels, resulting in considerable economic and environmental benefits. Savings are attained in the smelting section, because converters, converter aisles with cranes, ladles and other equipment are not needed.

Batch operation of the PS converters generates large gas volumes at times, followed by periods with no gas at all. All the gas handling facilities, but especially the acid plant, must be designed to cope with the peak gas generation. In the DON technology, continuous gas flow with a low volume and high SO_2 concentration means lower investment costs especially in the gas cleaning section, but also in other areas of the sulfuric acid plant. Furthermore, the oxygen plant required by the DON concept is smaller in capacity than in the conventional methods, which reduces the capital costs in favor of the DON option.

We have estimated capital as well as operating costs of two nickel smelters, one applying the conventional Flash Smelting-PS Converting route and the other using the DON process concept. Both smelters produce nickel matte with a capacity of 70 000 mtpa nickel. According to our cost comparison, the overall saving in capital costs in favor of the DON technology is about 15 %. Reduction in the operating costs is of the same order of magnitude.

Environment and Occupational Hygiene

One major advantage of the DON technology is a lower treatment cost of sulfur dioxide gases. The smelting process produces only one continuous, concentrated SO₂ -gas stream, when the fluctuating PS converter gas flow is eliminated. Batch operation with ladle transportation of molten materials is a significant source of fugitive gas and dust emissions. The DON smelting is almost continuous and no ladle transportation is needed, and matte as well as slag are transferred via covered and hooded launders. For these reasons the working conditions inside the plant can be kept clean and hygienic.

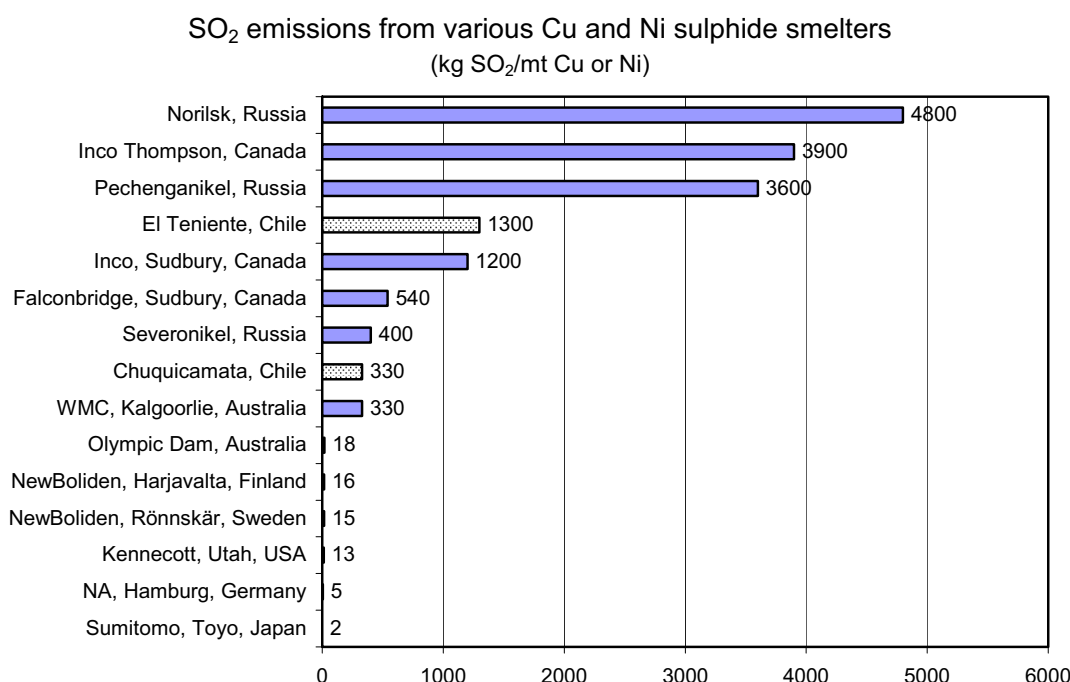


Figure 10. Nickel operations ■, copper operations □.

For example, the sulfur balance of the Harjavalta nickel smelter indicates that the sulfur recovery into saleable products and slag is 99.2 %. The changes in the smelting process and technology and installation of the new sulfuric acid plant have made it possible to meet the new occupational and environmental standards [2].

Relating to the specific sulfur emissions (kg SO₂/t metal) of nickel smelters, there are wide variations between the smelters as shown in Figure 10, which is based on various public sources. In some countries, a sulfur fixation of 90 % or even less is still sufficient. A few smelters operate today with very poor sulfur capture or even without any sulfur fixation at all.

Pressure to improve capture tends to come from national authorities. They can often impose standards that are higher than national limits, because of pressure from local residents. One can expect that the sulfur capture higher than 99 % will become more and more the standard in the near future. Thus many plants will need investments to improve their efficiency of sulfur collection. In nickel smelting, DON technology is the available answer for these requirements.

Intellectual Property Rights

Outokumpu Technology possesses all the intellectual property rights of Outokumpu Nickel Process technologies covering both the smelter and refinery areas. To successfully transfer the knowledge to a client Outokumpu Technology uses a specific TT system [20], based on a good collaboration with the parties. Its main advantages are a shorter project implementation time, cost savings, share of responsibilities and risk as well as wide guarantees.

TT covers the total technology package, including the basic engineering, training, supply of the technology related equipment and supervision for the construction and commissioning. Only in this way the transfer of the existing know-how will be secured, a tight implementation time schedule will be met and Outokumpu Technology as a technology supplier can provide the performance guarantees for the process as well as for the equipment. All the above elements are essential to make the technology transfer successful.

Conclusions

Pyrometallurgical methods dominate today as well as in the future the primary step of nickel processing. Outokumpu flash smelting technologies process about half of the world sulfidic nickel concentrates. The nickel refining technology by Outokumpu has been developed in parallel with the smelting technology to efficiently treat the various sulfidic concentrates and secondary raw materials to sellable nickel and other metal products.

The Outokumpu nickel flash smelting and refinery technologies have been in operation now for 45 years. During that time the processes and equipment have been intensively developed, and long-term experience as well as know how have been accumulated from various industrial operations. The major areas of the DON development have been:

- the properties of various nickel mattes, their fluidity and melting or solidification points, focusing at
 - furnace integrity, hearth design and cooling systems
 - EF-matte sulfurisation techniques.
- fundamentals of nickel smelting slag fluxing chemistry for high-MgO raw materials with the aim of evaluating
 - the operational window available in smelting and slag cleaning
 - maximized metal value recoveries.

Thus, several technology and process options are available for various types of sulfide concentrates, nickel mattes and secondary materials, to fulfill the customers' raw material and product requirements. At the same time, the plants using the Outokumpu nickel technology have successfully conformed to the local conditions with strong economical as well as environmental pressures and requirements.

The unique features of Outokumpu's Direct Nickel smelting technology are:

- high recoveries of nickel and especially cobalt and PGM's by minimizing unnecessary molten material circulation
- no internal molten material circulation and transfer by eliminating the furnace matte converting step from the smelting circuit
- high degree of sulfur fixation from a single and continuous off-gas flow
- minimum sulfur and dust emissions to the environment and working atmosphere.

These features of the state-of-the art nickel smelting and refining technology lead to possibility to optimise the process concept and the operation mode as well as to flexibility in treating a wide range of raw materials. The outcome is a low investment and operating cost smelter, acid plant and the refinery.

Outokumpu Technology possesses the intellectual property rights of the Outokumpu Nickel technologies covering both the smelter and refinery areas. The technology transfer to the customer is realized by a Technology Transfer system, based on a close collaboration guarantees the transfer of existing know-how and secures the efficient start of the operation.

Acknowledgements

The DON technology development over the years 1990-2005 has been a huge team-work by several engineers and scientists, which never can be too much emphasized. The project team is indebted to National Technology Agency (Finland) for its kind support to building the advanced knowledge base for this challenging task, including the development of advanced thermo-chemical databases and CFD sub-models.

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