



## ISASMELT™ TSL – Applications for nickel

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### ABSTRACT

The ISASMELT™ process is a top submerged lance (TSL) bath smelting technology which has been developed and optimised over the last 25 years. By the end of 2011, the total installed capacity of the ISASMELT™ technology will exceed 9,000,000 tonnes per year of feed materials in copper and lead smelters around the world. The technology is equally effective for smelting nickel sulfide concentrates, converting nickel mattes, and producing ferronickel from lateritic ores. This paper demonstrates how the features that make ISASMELT™ attractive for copper and lead smelting may be applied equally to nickel smelting and converting operations. Conceptual flowsheets are presented, supported by results from recent pilot plant and bench-scale testwork.

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### 1. Introduction

The introduction of lance technology has enabled the use of stationary furnaces of simple design and very high reaction rates. The prior art involved the injection of gases into liquid slags or mattes predominantly through tuyeres, with inherent design complications and refractory problems. The top submerged lance (TSL) bath smelting technology was developed to commercial success at the Mount Isa smelting complex in Australia in the early 1990s, and subsequently called “ISASMELT™”. Development of the process has focussed on smelting of lead and copper concentrates or secondaries over the last 30 years and commercial ISASMELT™ furnaces operated by Xstrata and external licensees currently have a combined annual smelting capacity exceeding 9,000,000 tonnes of feed.

### 2. The ISASMELT™ process

ISASMELT™ technology is based on a furnace design which is readily enclosed to eliminate emissions to the surrounding environment. It uses submerged lance injection technology to provide highly efficient mixing and reaction of feed materials in a molten slag bath. The use of advanced process control systems results in the furnace operation being largely automated. Being a vertical furnace, a very small footprint of floor space is required to accommodate the plant and so it can generally be easily retro-fitted into existing smelters to either augment or replace existing technology. The process concept is shown in Fig. 1.

During 30 years developing and operating submerged lance technology on large scale plants, significant technical improvements have occurred in areas such as furnace design, feed preparation systems, off-gas handling, operating and process control strategies, refractory management and operator training. The combined experience led to what is well recognised by the marketplace today as the “ISASMELT™ technology package”, a technology package licensed to external clients – Burford (2009). Many of the improvements implemented by plant operators have been passed onto, and adopted by, other licensees. Exchange of ideas and technical improvements occurs through ad hoc visits to fellow licensee sites and through regular licensee workshops arranged by Xstrata Technology. Fig. 2 shows the location of the commercial plants that have been licensed to date.

### 3. Agip nickel ISASMELT™ plant

It is less well known that the ISASMELT™ process was also adapted for the treatment of nickel bearing feeds at a very early stage of its development. A large amount of pilot-scale testwork was completed during the 1980s on nickel deposits owned by Mount Isa Mines Ltd. Testwork was also performed for AGIP Australia Pty Ltd., who owned the Radio Hill deposit in Western Australia – Bakker et al. (2009). In 1991, AGIP decided to construct a semi-commercial ISASMELT™ plant to produce nickel–copper matte from concentrate feed. This was the first ISASMELT™ plant built and commissioned for an external client. Earlier in 1991, the first commercial-scale ISASMELT™ plant had been commissioned to produce lead bullion from concentrates in Mount Isa. A year later, two commercial-scale ISASMELT™ plants were commissioned to produce copper matte from concentrates; one in Mount Isa and the other in Miami, Arizona.

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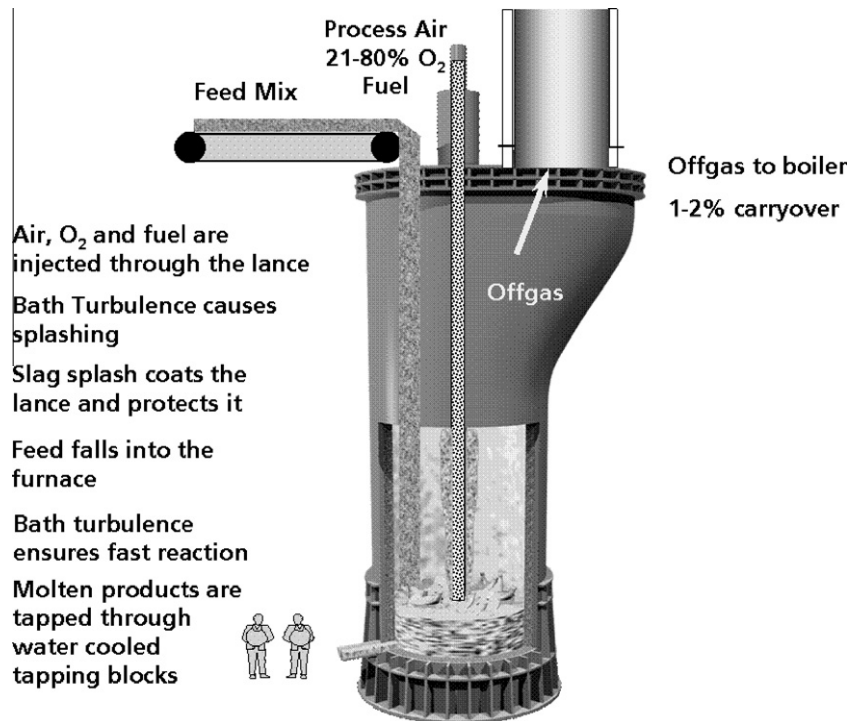


Fig. 1. The ISASMELT™ concept.

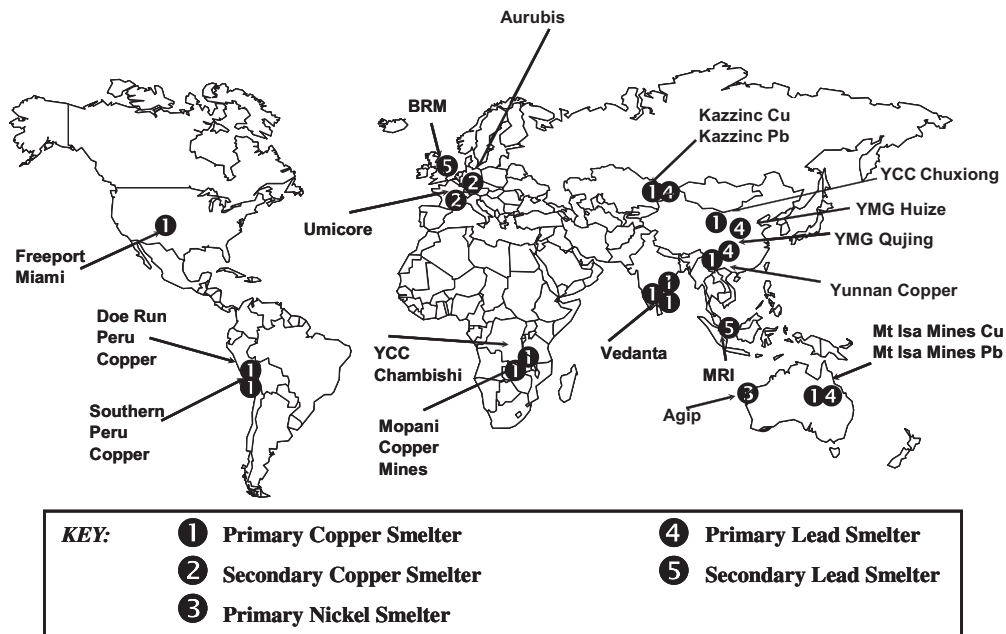


Fig. 2. ISASMELT™ plant locations.

The AGIP nickel ISASMELT™ commercial-scale plant was commissioned in September 1991 and within 3 months was running at design capacity of 7.5 t/h concentrate – Arthur and Hunt (2005). It produced 45 wt% nickel/copper matte from a concentrate containing approximately 7 wt% nickel and 3.5 wt% copper. Photographs of the plant are shown in Fig. 3 – Bakker et al. (2009). At the time, the plant was deemed a technical and operational success, however due to a large drop in nickel price, the facility was forced to close near the end of 1991; the plant has since been demolished.

#### 4. The ISACONVERT™ process

A combination of pilot plant copper and nickel–copper continuous converting trials and the commercial batch copper converting operations show the ISASMELT™ furnace to be well suited to the duty of continuous converting – the ISACONVERT™ furnace – Edwards and Alvear (2007).

The ISACONVERT™ technology is based on the same design as the ISASMELT™ furnace which allows it to be readily enclosed to eliminate emissions to the surrounding environment. It uses the

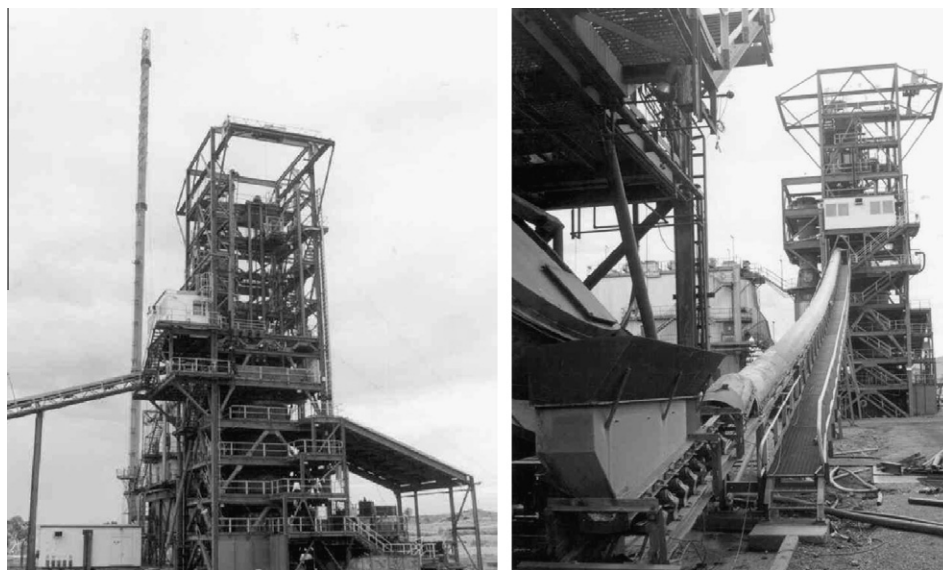


Fig. 3. Photographs of AGIP nickel ISASMELT™ plant.

submerged lance injection technology to provide highly efficient mixing and reaction of solid matte and flux, which is dropped in through the roof of the furnace. As with the ISASMELT™ furnace the ISACONVERT™ has a small footprint of floor space and can generally be easily retro-fitted into existing smelters.

The union between recent applied research and pioneering pilot plant work has made possible the industrial-scale implementation of the ISACONVERT™ process – Nikolic et al. (2009). A cutaway image of an ISACONVERT™ plant is shown in Fig. 4.

Application of both the ISASMELT™ and ISACONVERT™ furnace technology to copper production allows for a very compact site that requires significantly less area than a conventional copper smelter. The fact that the smelting and converting processes are very similar and easy to control via a proven robust process control system also simplifies operations and logistics within the smelter, allowing all operations to be carried out from one central control room. These factors lower the operating costs of a new smelter compared with the conventional Peirce–Smith technology. The sig-

nificantly reduced off-gas volume from the ISACONVERT™ process will result in lower capital and operating costs for off-gas collection and cleaning systems.

### 5. Nickel ISASMELT™ sulfide smelting process concept

The feed to a nickel sulfide smelter typically consists of a nickel–copper concentrate, which may also contain minor amounts of cobalt and platinum group metals. The smelting product from such feeds is generally a primary, high iron smelting matte which is further processed, typically in Peirce–Smith converters, to produce finished, high grade matte, often referred to as “Bessemer matte”.

The 2007 TMS survey of worldwide nickel sulfide smelters reported that flash smelting accounted for approximately 70% of nickel smelter output (based on 2004–2005 reporting data), with electric furnace smelting representing the balance – Warner et al. (2007). However, the same features that make the ISASMELT™ process an attractive alternative for copper and lead smelting can be equally applied to nickel smelting – Bakker et al. (2009).

The basic process block diagram for a primary smelting nickel ISASMELT™ plant is shown in Fig. 4. The nickel ISASMELT™ furnace continuously processes concentrate feed, fluxes, and recycled dust. The product liquid matte and slag is tapped periodically from the ISASMELT™ vessel to a separate slag cleaning furnace via a single taphole. Off-gases from the ISASMELT™ furnace are directed to a waste heat boiler for heat recovery and de-dusted using an electro-static precipitator before being sent to a sulfuric acid plant for sulfur capture. The primary smelting matte is transferred by ladles from the settling furnace to the Peirce–Smith converters for production of Bessemer matte; alternatively continuous converting could be used, refer below. Discard slag is also intermittently tapped from the settling furnace for disposal. All dusts collected from the gas handling systems are recycled to the ISASMELT™ furnace.

The possibility of using the nickel ISASMELT™ process to produce Bessemer matte with low iron content directly from concentrate feed is also shown in Fig. 4, as a dotted line. This would obviate the need for Peirce–Smith converting altogether. The direct nickel ISASMELT™ process is similar to the Direct Outokumpu Nickel (DON) process where the metal values in the smelting slag are recovered in the slag cleaning furnace. The DON process was first applied to the Harjavalta plant in Finland in 1995 and then



Fig. 4. Cutaway of a design for the ISACONVERT™ furnace.

at a much smaller scale at the Fortaleza plant in Brazil in 1998 – Mäkinen and Taskinen (2006). The nickel ISASMELT™ thus has the flexibility to produce either primary smelting matte (Fe in matte greater than 15 wt%) or Bessemer matte (Fe in matte less than 4 wt%) depending on the customer's requirements.

## 6. Nickel ISACONVERT™ process concept

Matte generated from the primary smelting of nickel concentrate is almost exclusively processed to Bessemer matte using multiple units of Peirce–Smith converters. The exceptions are the Anglo Platinum Watervale smelter in South Africa, where the Anglo Platinum Converting Process (ACP) is employed and Stillwater Mining Company smelter in Montana, USA, where top blown rotary converters are used. In both cases, the respective converting processes treat granulated primary smelting matte, however, of the two, only the ACP is fed continuously.

Continuous nickel converting is not a new concept and has been investigated previously for improved productivity and emission control compared to the traditional Peirce–Smith batch converters. As noted above the ACP plant has already commercialised the basic process concept. In addition, Vale Inco has for over a decade carried out a substantial research and development program investigating continuous nickel converting – Warner and Diaz (2003). Over about this period, Vale Inco investigated three approaches for continuous converting; their own flash converting (Victorovich (1993)), oxygen top blowing–nitrogen bottom stirring bath converting technology, and using Noranda/El Teniente type bath converting technology (Donald et al. (2005)). It is noted that the primary goal in this work was to develop a continuous converting technology applicable for the Copper Cliff, Ontario nickel plant, where downstream refining requires a very low, 0.5 wt%, iron in matte. While technically feasible, in the tests (Donald et al. 2005) the more oxidized slag produced at this low iron content proved somewhat problematic; instead preference was given to a “two-stage” approach involving continuous converting to about 2–3% Fe, followed by batch finishing for final matte grade adjustment.

It is in the production of Bessemer mattes, down to less than 4 wt% iron, where the ISACONVERT™ is seen to have a niche. The

basic process block diagram for a nickel ISACONVERT™ plant is shown in Fig. 5. It should be noted that the nickel ISACONVERT™ process is a truly continuous converting process with matte and air/oxygen continuously fed to the bath. The bath consists of the converting products at all times, as the operating conditions effectively fix the process at what is, for Peirce–Smith converters, the end point of the converting reactions.

The nickel ISACONVERT™ furnace continuously processes primary smelting matte feed, fluxes along with recycled slag cleaner matte and dusts. The product liquid Bessemer matte is tapped periodically from the matte taphole to: (1) A granulation system or, (2) Slow cooling system (depending on refinery). Slag is tapped from a separate taphole from the ISACONVERT™ vessel to a separate slag cleaning furnace where metal values are recovered by adding reductant (coke and/or concentrate) to produce a separate matte and a cleaned slag phase. The matte from the slag cleaning furnace is granulated and recycled to the ISACONVERT™ furnace, whereas the slag is discarded. Off-gases from the ISACONVERT™ furnace are directed to a waste heat boiler for heat recovery and de-dusted using an electro-static precipitator before being sent to a sulfuric acid plant for sulfur capture. All dusts collected from the gas handling systems are recycled to the ISACONVERT™ furnace.

The presented nickel ISACONVERT™ process offers two important advantages compared with the traditional batch Peirce–Smith Converting.

The first advantage of the ISACONVERT™ process is the generation of a constant volume of high strength SO<sub>2</sub>-containing gases that can be treated in a conventional sulfuric acid plant. This is an important benefit considering current and future stringent environmental regulations affecting both plant emissions and in-plant hygiene. While fitting tight converter hoods remains the option to maintain adequate SO<sub>2</sub> levels in converter off-gas, this approach coupled with the additional need for secondary hooding to control fugitives emissions all add to the overall cost of Peirce–Smith converters. The ISACONVERT™ offers a one-step converting process that can utilize high levels of oxygen enrichment coupled with minimal air dilution, thus producing a lower volume off-gas readily amenable to treatment in a sulfuric acid plant.

A second advantage is the flexibility offered by the use of solid matte as the feed material, thus eliminating ladle transfers, and

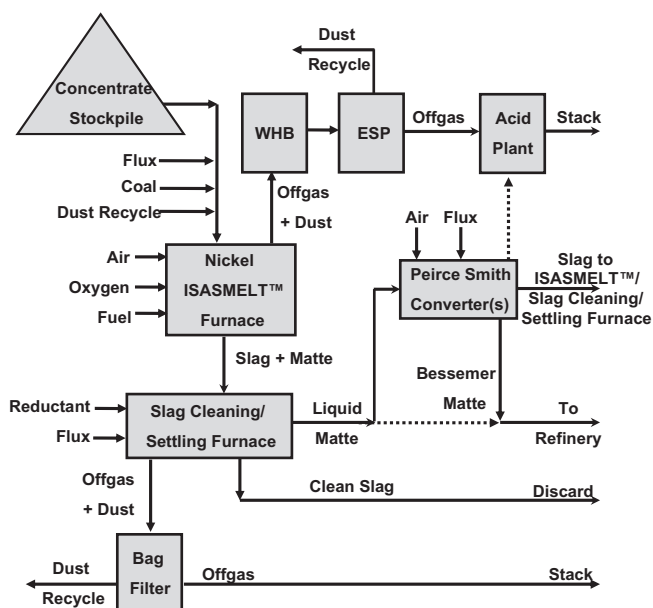


Fig. 5. Process block diagram for a nickel ISASMELT™ plant.

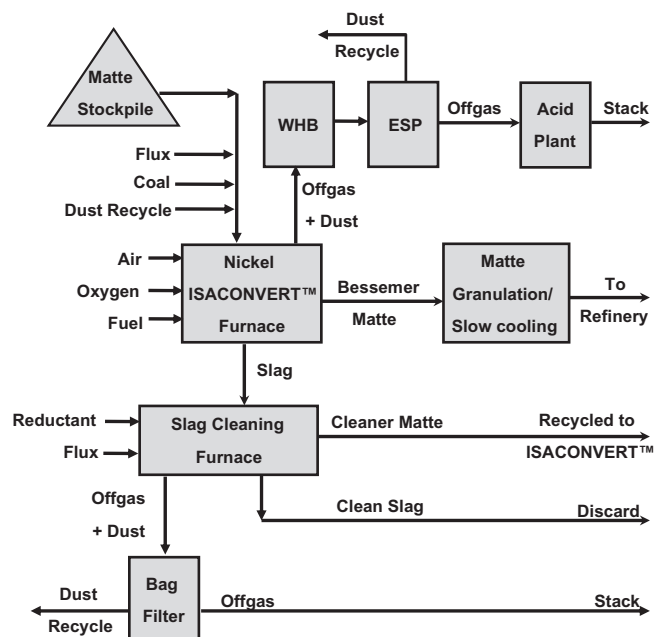


Fig. 6. Process block diagram for a nickel ISACONVERT™ plant.



further lowering opportunities for fugitive emissions with the resulting improvement in-plant hygiene. Further, the use of solid/granulated feed allows decoupling of the smelting and converting steps, giving added flexibility and simplifies the maintenance and operational aspects of the smelter.

## 7. Nickel ISASMELT™ laterite smelting process concept

The 2007 TMS survey of worldwide nickel laterite smelters reported that the Rotary Kiln-Electric Furnace technology (RKEF) is almost exclusively used for the smelting/reduction of nickel-bearing laterites – Warner et al. (2006). The RKEF process typically treats a low-iron magnesium–aluminium–silicate saprolite material (or sometimes a “transitional” material); the electric furnace (EF) products are a ferro-nickel alloy for the market (after refining) and a discard slag. In some cases, sulfur is added at the reduction kiln, thus producing a low sulfur matte at the EF which is finished to a Bessemer matte by conventional converting. The ISASMELT™ technology has recently been investigated for the smelting of these type of nickel laterite ores.

The basic process block diagram for a nickel laterite smelting ISASMELT™ plant is shown in Fig. 7. The ISASMELT™ furnace continuously processes dried laterite feed and recycled dust, with the smelting heat provided by coal and oxygen-enriched air; flux addition may be considered depending on the ore used. The product liquid alloy and slag are periodically tapped via a single taphole from the ISASMELT™ vessel to a separate slag settling/cleaning furnace. Alternatively the ISASMELT™ furnace can be used for smelting/pre-reduction, maximising fuel energy usage, with the majority of the reduction, and therefore nickel alloy generation, completed in the slag cleaning furnace. Another variation would be to include a calcination step, for example, using a flash calciner before the ISASMELT™ unit. ISASMELT™ off-gases can be post-combusted in the upper section of the furnace (with the addition of some oxygen-enriched air as required), imparting heat to the incoming feed. Off-gases from the top of the ISASMELT™ furnace are then directed to a waste heat boiler for heat recovery and de-dusted using an electro-static precipitator before being sent to the site stack. The product liquid ferro-nickel alloy is periodically

tapped from the electric furnace to: (i) A granulation system, or (ii) A casting system (depending on product specifications), or (iii) A hot metal ladle for further refining as needed. Discard slag is also intermittently tapped from the settling furnace for disposal; and advantageously if required, heat recovery. All dusts collected from the gas handling processes are recycled to the ISASMELT™ furnace.

An alternative option to this flowsheet involves the addition of a sulfur-bearing feed (refer to dotted lines and process units in Fig. 6), that can be added to the ISASMELT™ furnace bulk feed to allow for the production of a low-iron matte.

## 8. Nickel ISASMELT™ pilot plant trials

Several more recent campaigns of trials using an ISASMELT™ pilot plant have been conducted to provide further data regarding the operability of the:

- (i) ISASMELT™ process involving the smelting of nickel/copper concentrates to either a high iron primary smelting matte or Bessemer matte;
- (ii) ISACONVERT™ process involving the converting of primary high iron smelting nickel/copper matte to Bessemer matte; and
- (iii) ISASMELT™ process involving the smelting of nickel laterite ores to a ferro-nickel alloy, involving both pilot and bench-scale tests.

The main objectives of these tests were to determine the product nickel matte/alloy and slag compositions, elemental partition ratios between matte/alloy and slag (particularly nickel and cobalt), and generate slags for subsequent slag cleaning testwork.

### 8.1. The ISASMELT™ pilot plant

The pilot ISASMELT™ facilities consist of a stationary cylindrical furnace with an internal diameter (within refractory) of approximately 400 mm and a height of approximately 2000 mm. The vessel is lined with chrome–magnesite refractory bricks, and is backed by high alumina insulation bricks. During operation, the furnace contains a molten bath having a maximum depth of about 600 mm. Controlled amounts of air and oxygen are injected into the bath via either a 32 mm (1.25 inch) or 38 mm (1.5 inch) stainless steel lance. The feed is added in known amounts to a calibrated variable speed conveyor belt which drops the feed through a chute at the top of the furnace at a rate typically between 100 kg/h and 250 kg/h. Fuel oil is injected down the lance to control bath temperature. In some cases, solid coal may also be added. Removal of molten products can be achieved by opening one of two tapholes and collecting the materials in cast iron ladles. The process off-gases are cooled and de-dusted before being directed to a caustic soda scrubber for removal of any sulfur-containing gases prior to venting to stack.

### 8.2. Nickel ISASMELT™ smelting trials

Nickel concentrates were successfully smelted to produce mattes over a wide range of iron contents; from 1.6 wt% Fe to 20.0 wt% Fe. The purpose of the testwork was to demonstrate the process flexibility for the production of matte at any grade required by the customer, ranging in composition from primary smelting matte (Fe in matte greater than 15 wt%) to Bessemer matte (Fe in matte less than 2–4 wt%) from feed concentrates. The typical nickel/copper concentrate feed composition is shown in Table 1.

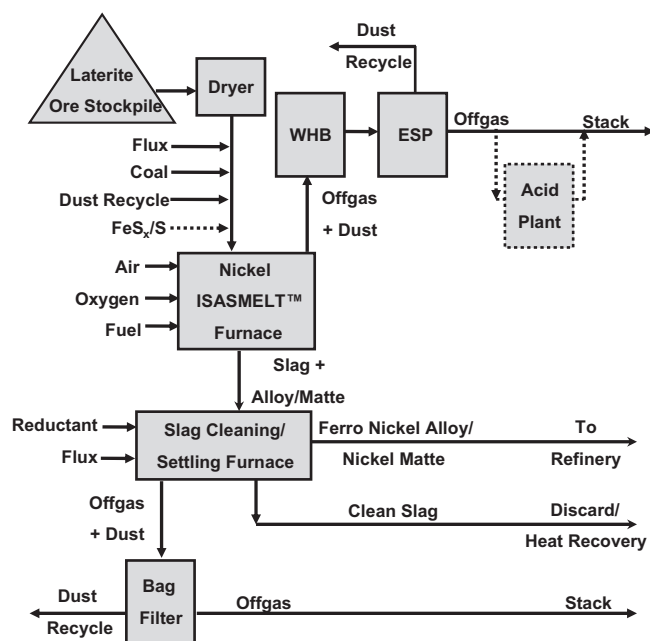


Fig. 7. Process block diagram for a nickel laterite ISASMELT™ plant.

**Table 1**  
Nickel/copper concentrate feed composition.

Element	Average content (wt%)
Ni	17.1
Cu	4.3
Co	0.4
Fe	31.0
S	27.0
SiO <sub>2</sub>	9.8
MgO	6.5
Al <sub>2</sub> O <sub>3</sub>	1.0
CaO	0.7

**Table 2**  
Range of ISASMELT™ slag compositions.

Element	Range (wt%)
Ni	0.8–7.0
Cu	0.3–1.5
Co	0.2–0.3
Fe	32.0–37.6
SiO <sub>2</sub>	25.6–34.9
MgO	6.7–10.3
Al <sub>2</sub> O <sub>3</sub>	3.8–5.1
CaO	1.4–2.5

The concentrate was pelletised with pre-determined amounts of silica flux (according to the planned slag composition) and charged to the furnace at a rate equivalent to 150 kg/h of wet concentrate. Granular coal was typically added to the feedbelt at a rate equivalent to 5% of the concentrate feedrate to provide additional smelting heat, due to the heat loss term associated with the size of the pilot-scale furnace. Smelting air and oxygen were metered through separate rotameters at a ratio to yield 40–45 v/v% total oxygen. Fuel oil was injected down the lance as trim fuel to maintain the bath temperatures between 1310 °C and 1450 °C, depending on the test conditions.

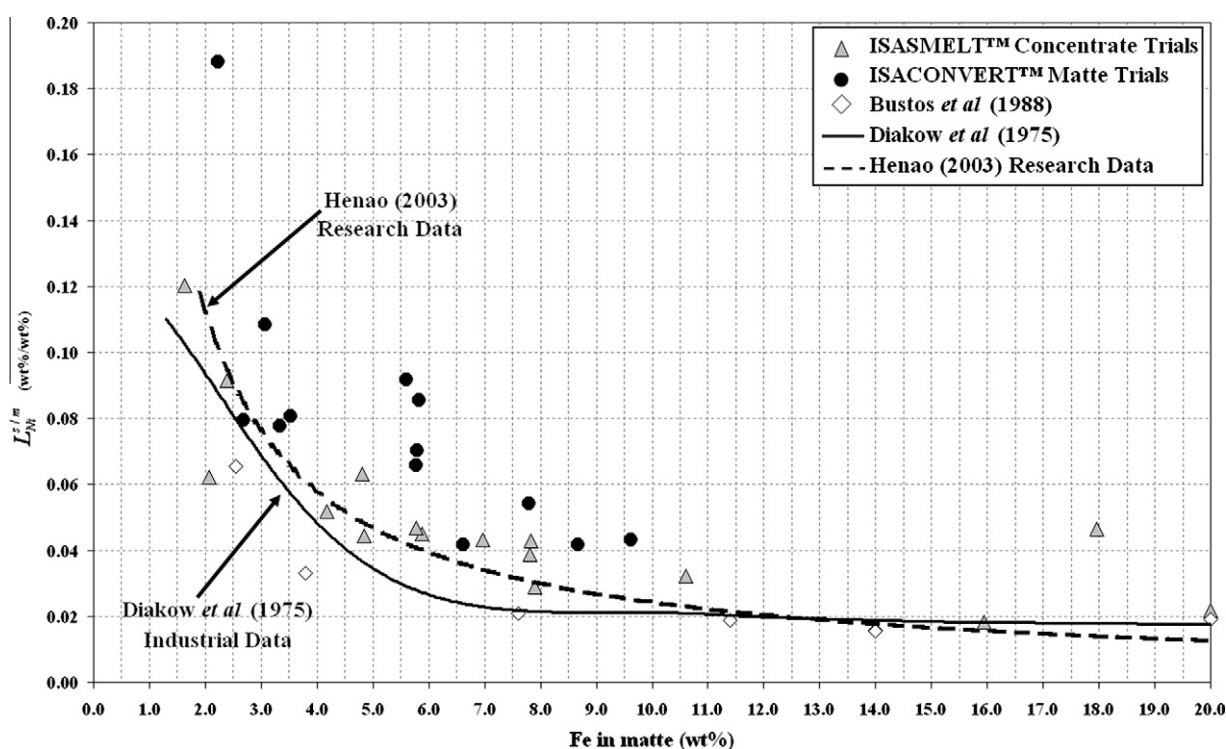
Fluid slags were produced under all test conditions. The iron-silica ratio in ISASMELT™ slag generated during the tests ranged from 0.9 to 1.4. Compositional ranges for the ISASMELT™ slag for the tests are shown in Table 2.

The distribution coefficients for nickel, as defined by Eq. (1) below, are shown as a function of iron content in bulk matte in Fig. 7, both for the ISASMELT™ and ISACONVERT™ tests (discussed later in the ISACONVERT™ trials section). The bulk matte and slag were analysed from spoon samples taken during tapping.

$$L_X^{s/m} = (\text{wt}\% \times \text{in slag}) / (\text{wt}\% \times \text{in matte}) \quad (1)$$

Included in Fig. 7 for comparison are the laboratory results of Henao (2003) and the results obtained during a sampling campaign of a Peirce–Smith blow on nickel-copper matte at the Xstrata Nickel (XNi) Falconbridge smelter (Bustos et al. (1988)) and at the Vale Inco Thompson smelter (Diakow et al. (1975)). In Henao's work, a matte-slag melt was equilibrated at 1500 °C or 1600 °C for a given time period at a specific fixed oxygen (P<sub>O2</sub>) and sulfur dioxide (P<sub>SO2</sub>) atmosphere (set by S<sub>2</sub>/SO<sub>2</sub> and CO/CO<sub>2</sub> ratio control). At the end of each equilibrated test, quenched samples of matte and slag were taken for assay. The XNi Falconbridge and Vale Inco Thompson smelter data were obtained by sampling the matte and slag in the converter at the end of each individual blow. Interestingly, all the data in Fig. 7 compare very well.

The distribution coefficients for cobalt, as defined by Eq. (1), are shown in Fig. 8 as a function of the iron content of matte for the ISASMELT™ and ISACONVERT™ tests. Included in Fig. 8 for comparison are the laboratory results of Font (1999) and, as per Fig. 7 the industrial data from Bustos et al. (1988) and Diakow et al. (1975). In Font (1999)'s work, a matte-slag melt was equilibrated (as in Henao (2003)'s later work noted above) for a given time at a specific fixed oxygen (P<sub>O2</sub>) and sulfur dioxide (P<sub>SO2</sub>) atmosphere (set by S<sub>2</sub>/SO<sub>2</sub> and CO/CO<sub>2</sub> ratio control). At the end of each test, quenched samples of matte and slag were taken for assay.



**Fig. 8.** Nickel in slag as a function of iron in ISASMELT™ matte.

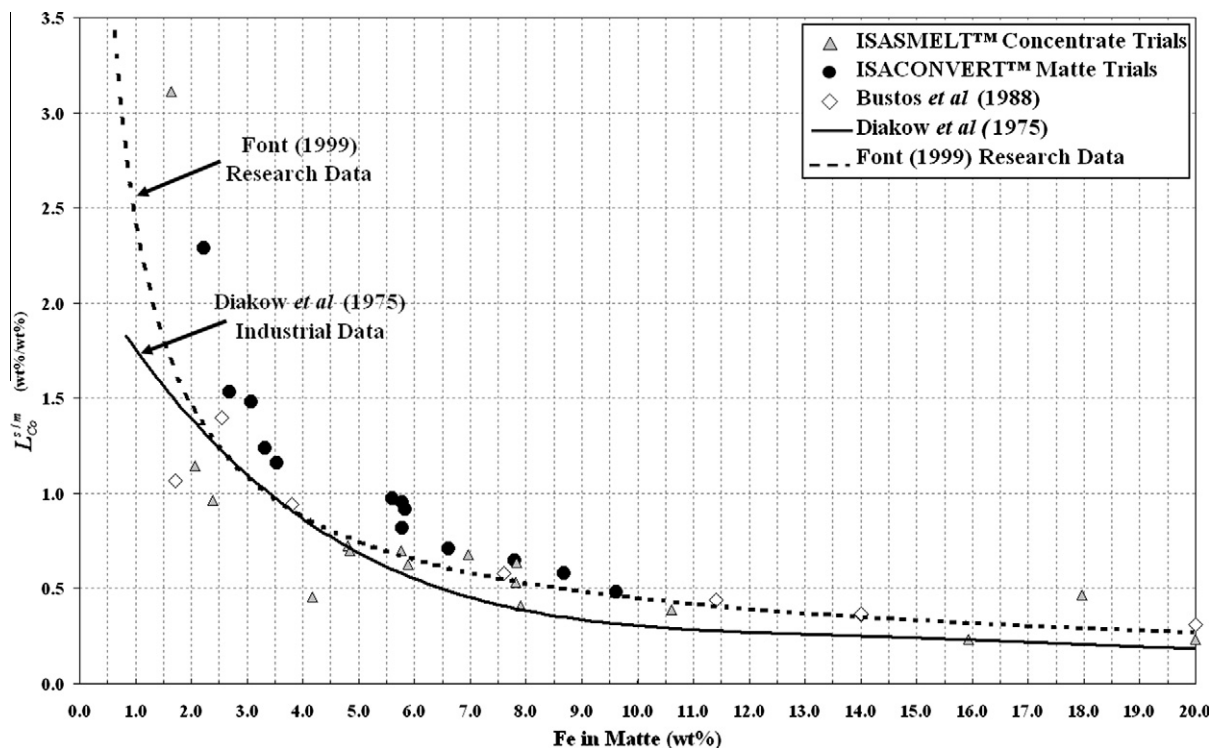


Fig. 9. Cobalt distribution as a function of iron in ISASMELT™ matte.

The XNi Falconbridge and Vale Inco Thompson smelter data here were obtained by the same method as described for Fig. 7. As with Fig. 7, it is of interest to note that all data in Fig. 8 for cobalt distribution between slag and matte compare very well.

Figs. 7 and 8 shows that with decreasing iron levels in matte, both the nickel and cobalt slag/matte distribution coefficients increase. This is as expected due to the higher oxygen potential ( $P_{O_2}$ ) of the system associated with lower iron levels in matte. Further as noted, the data in Figs. 7 and 8 shows that there is good agreement between the pilot plant results for both the ISASMELT™ and ISACONVERT™ trials and previously published data for somewhat similar matte-slag systems.

In order to provide information on the slag liquidus temperatures for slags encountered in the pilot plant trials, the FactSage™ (Bale et al. (2002)) package was used to evaluate phase equilibria in the NiO–MgO–FeO–Fe<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub>–Al<sub>2</sub>O<sub>3</sub>–CaO slag system. The results of the FactSage™ calculations at the conditions of:  $P_{O_2} = 10^{-7.6}$  atm, Al<sub>2</sub>O<sub>3</sub> = 4 wt%, CaO = 1.5 wt% and MgO = 10 wt% are shown on the pseudo-ternary NiO–FeO–SiO<sub>2</sub> diagram in Fig. 9. The FactSage™ liquidus calculations and slag compositions from the pilot trials were plotted by normalising to the axes of the pseudo-ternary graph. It can be seen that all slags encountered in the tests were predicted to lie within the olivine primary phase field (p.p.f.).

### 8.3. Nickel ISACONVERT™ trials

The purpose of the converting testwork was to demonstrate the ISACONVERT™ process for converting solid high iron primary smelting matte feed to low iron Bessemer mattes. The typical primary smelting matte composition is shown in Table 3. As will be shown, the primary smelting mattes were successfully converted to produce finished mattes with iron contents from 2.2 wt% Fe to 9.6 wt% Fe.

In the tests, matte with a pre-determined amount of high silica flux (set according to the target iron to silica ratio in slag) was charged to the furnace at a rate equivalent to 200 kg/h of “as received” solid matte. Granular coal was added to the feedbelt at a rate equivalent to 5% of the matte feed rate, due to similar considerations as mentioned in pilot-smelting. Converting air and oxygen were metered through separate rotameters at a ratio to yield 35–40 v/v% total oxygen enrichment. As with the smelting tests, fuel oil was injected down the lance as trim fuel to maintain the bath temperatures between 1310 °C and 1380 °C depending on the test conditions.

It was found that fluid slags were produced under all test conditions over a range of iron–silica ratios in ISACONVERT™ slag from 1.1 to 2.3. Compositional ranges for the ISACONVERT™ slag for the tests are shown in Table 4.

**Table 3**  
Primary smelting nickel matte composition.

Element	Average content (wt%)
Ni	44.5
Cu	9.7
Co	2.9
Fe	25.3
S	17.2
SiO <sub>2</sub>	0.3

**Table 4**  
Range of ISACONVERT™ slag compositions.

Element	Range (wt%)
Ni	2.2–6.4
Cu	0.6–1.2
Co	1.3–2.5
Fe	37.8–48.0
SiO <sub>2</sub>	25.6–34.9

As noted above, the level of nickel in slag and the slag/matte cobalt distribution coefficient for the ISACONVERT™ tests are included in Figs. 7 and 8. The nickel ISACONVERT™ tests aimed to achieve low iron content in matte. As evident in Fig. 7, the Ni level in slag rises significantly towards the low Fe matte composition. On account of the more oxidized conditions at low iron levels in matte, the slag under these conditions has a higher liquidus. However in this case, the Fe/SiO<sub>2</sub> can be trimmed to lower the liquidus temperature.

As with the smelting tests, the FactSage™ (Bale et al. (2002)) package was also used for the converting conditions to predict the liquidus temperatures in the slag system using the simplified NiO–FeO–Fe<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub>–Al<sub>2</sub>O<sub>3</sub>–CaO–MgO system. The predictions were projected, through normalisation of the data, onto the pseudo-ternary NiO–FeO–SiO<sub>2</sub> system in Fig. 10. The following conditions were used for the FactSage™ calculations: Po<sub>2</sub> = 10<sup>−7.6</sup> atm, Al<sub>2</sub>O<sub>3</sub> = 2.5 wt%, CaO = 1.5 wt%, and MgO = 2.5 wt%. The compositions of the final ISACONVERT™ slags are plotted together with the liquidus predictions in Fig. 10. Similar to the ISASMELT™ slags, most of the ISACONVERT™ slags were within the olivine primary phase field (p.p.f.).

#### 8.4. Nickel laterite ISASMELT™ trials

The purpose of the laterite smelting testwork was to demonstrate the production of a ferro-nickel alloy at both the bench and pilot-scale. The campaigns were undertaken on two separate laterite deposits that were not related by geographical location. The typical compositional ranges for the two laterite ores used for the work are shown in Table 5. These laterite ores were successfully smelted in the tests under reducing conditions to produce a ferro-nickel alloy and a low nickel slag. The bench-scale trials produced ferro-nickel alloy grades between 15 and 40 wt% Ni with a starting SiO<sub>2</sub>/MgO and Fe/Ni ratios between 1.2–3.1 and 10–20 respectively. On the other hand, the pilot-scale trials produced ferro-nickel alloy grades between 60 and 85 wt% Ni with a starting SiO<sub>2</sub>/MgO and Fe/Ni ratios between 2.0–3.6 and 5–12 respectively.

The bench-scale tests were carried out batch-wise in small crucibles (holding approximately 1 kg of melt). After initial melting,

**Table 5**  
Nickel laterite feed compositions.

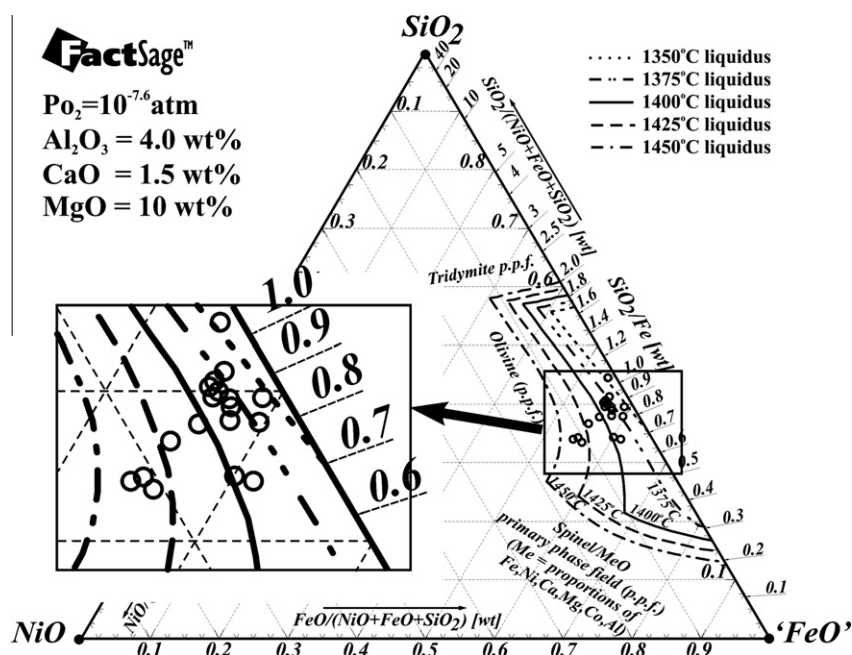
Element	Bench-scale testwork Average content (wt%)	Pilot-scale testwork Average content (wt%)
Ni	0.6–1.8	0.3–3.6
Fe	5.0–25	8.4–20.9
SiO <sub>2</sub>	22–46	40–46
MgO	12–25	12–22
Al <sub>2</sub> O <sub>3</sub>	2.5–8.5	0.7–3.0
CaO	0.1–1.1	0.2–2.5

the bath was reduced with the addition of coal over time. Due to the preliminary nature of the tests, a flux – high grade silica and/or limestone – was added to the ore to ensure the formation of a liquid slag. It is recognised that in practice, fluxing would not normally be carried out. For the pilot-scale trials, the laterite ore with silica and limestone flux were charged to the furnace at a rate equivalent to 150–200 kg/h of ore. Solid coal was added to the feedbelt for both reduction and to provide a portion of the required smelting energy. The balance of the heat to maintain the molten bath was supplied by fuel oil injected down the lance.

It was found that fluid slags were produced under all test conditions; the compositional ranges for the slags for both the bench-scale tests and the pilot-scale trials are shown in Table 6.

The trend of weight percent nickel in slag as a function of time, as the coal was added to the crucible melt, in the bench-scale tests is shown in Fig. 11. The bench-scale trials were targeted to achieve selected ferro-nickel grades, whilst at the same time producing low nickel contents in the slag. It was also found that the nickel level in slag was highly affected by the settling time. Operating temperature and flux addition can be optimized to minimise the settling requirement and maximise ferro-nickel alloy recovery.

The FactSage™ (Bale et al. (2002)) package was used to predict the liquidus temperatures for the laterite smelting slag conditions. The simplified FeO–Fe<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub>–Al<sub>2</sub>O<sub>3</sub>–CaO–MgO–Cr<sub>2</sub>O<sub>3</sub> system was used to represent these slags. Due to the low levels of nickel oxide in the slag after reduction, nickel was not taken into account in the FactSage™ calculations. The predictions were projected, through normalisation of the data, onto the pseudo-ternary



**Fig. 10.** Liquidus in the system NiO–FeO–SiO<sub>2</sub>–Al<sub>2</sub>O<sub>3</sub>–CaO–MgO at Po<sub>2</sub> = 10<sup>−7.6</sup> atm, Al<sub>2</sub>O<sub>3</sub> = 4.0 wt%, CaO = 1.5 wt% and MgO = 10 wt%.



**Table 6**

Range of ISASMELT™ nickel laterite slag compositions.

Element	Batch-scale testwork Average content (wt%)	Pilot-scale testwork Average content (wt%)
Ni	0.03–0.3	–
Fe	7.1–21	18–25
SiO <sub>2</sub>	35–50	44–50
MgO	20–27	14–18
Al <sub>2</sub> O <sub>3</sub>	5.0–6.9	2.6–3.3
CaO	2.8–8.6	0.2–2.3

MgO–FeO–SiO<sub>2</sub> system in Fig. 12. The following conditions were used for the FactSage™ calculations:  $P_{O_2} = 10^{-11.1}$  atm, Al<sub>2</sub>O<sub>3</sub> = 4.0 wt%, CaO = 0.2 wt%, and Cr<sub>2</sub>O<sub>3</sub> = 1.0 wt%. The range of laterite crucible-scale and pilot-scale compositions for the ISASMELT™ slags are plotted as a grey circle together with the FactSage™ liquidus predictions in Fig. 12. Depending on bulk slag composition and temperature, the primary phase field of the slag system in the highlighted region can be pyroxene, olivine or tridymite/cristobalite (see Fig. 13).

## 9. Future development

Xstrata Technology has demonstrated to date that the ISASMELT™ process is an attractive option for both primary and secondary copper and lead smelting. More than 9,000,000 tonnes per year of feed materials are processed in these ISASMELT™ furnaces in copper and lead smelters at smelters around the world. The features that make ISASMELT™ attractive for copper and lead smelting can be applied equally to nickel smelting and converting operations. The use of the ISASMELT™ process for copper/nickel smelting has already been successfully demonstrated on a commercial scale.

Recent ISASMELT™ and ISACONVERT™ pilot and batch-scale testwork described here has been successfully completed on the:

- ISASMELT™ process for producing primary high iron smelting matte and Bessemer matte directly from concentrates;
- ISACONVERT™ processes for production of Bessemer matte from high iron matte; and

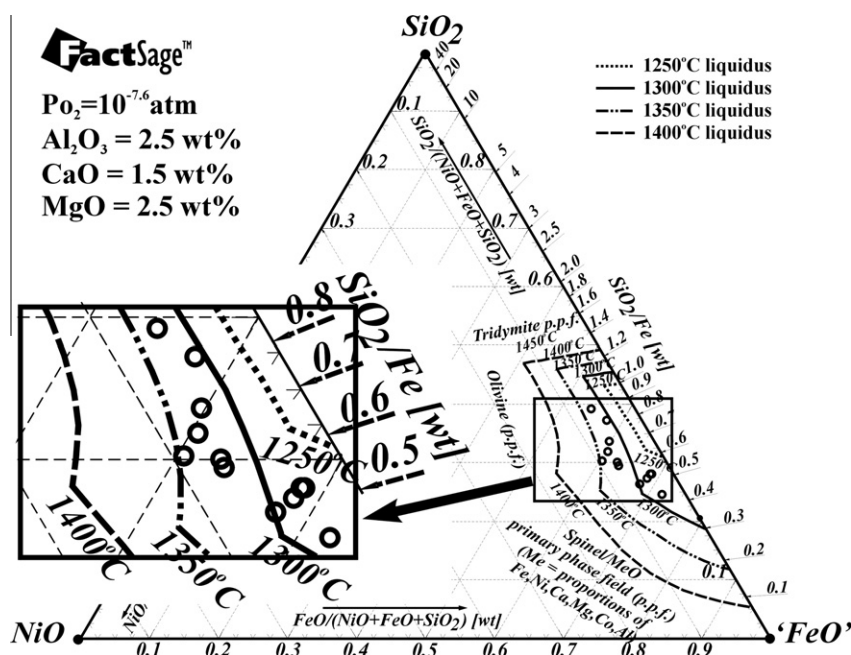


Fig. 11. Liquidus in the system NiO–FeO–SiO<sub>2</sub>–Al<sub>2</sub>O<sub>3</sub>–CaO–MgO at  $P_{O_2} = 10^{-7.6}$  atm, Al<sub>2</sub>O<sub>3</sub> = 2.5 wt%, CaO = 1.5 wt% and MgO = 2.5 wt%.

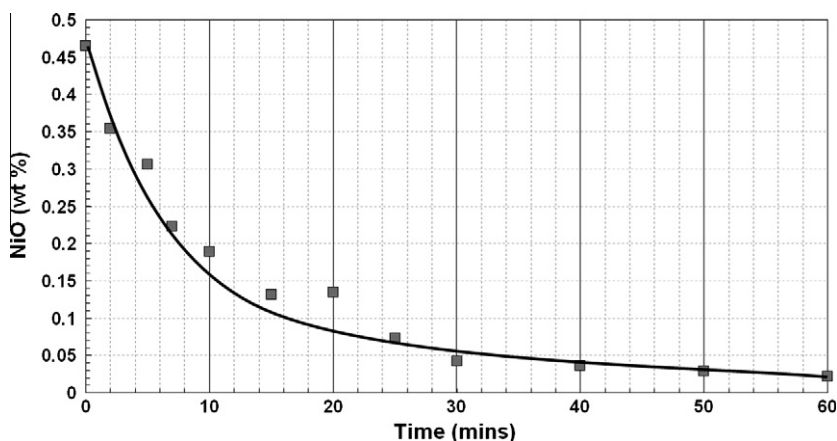


Fig. 12. Reduction of nickel from slag bath from Bench-scale testing.

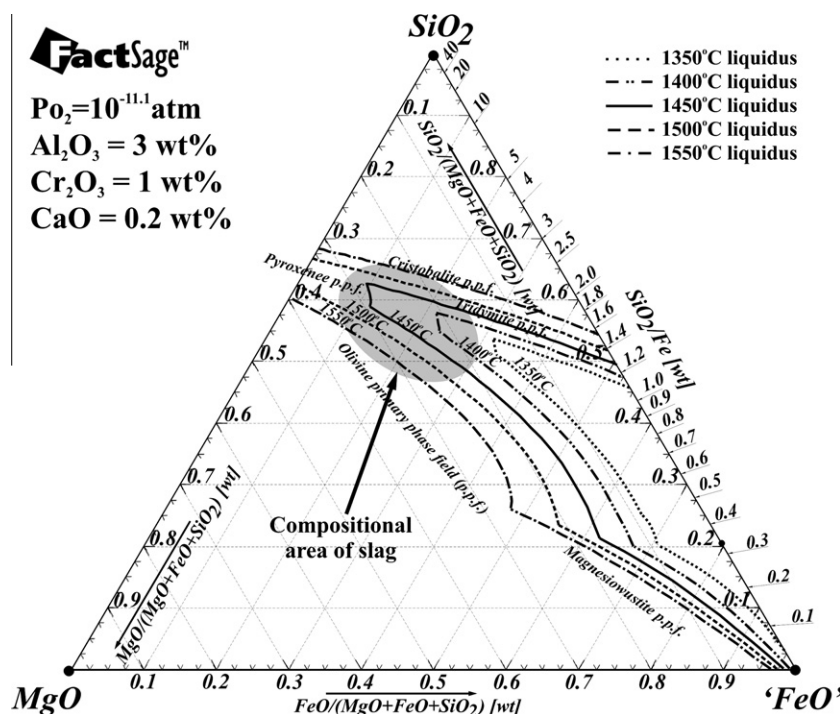


Fig. 13. Liquidus in the system FeO–Fe<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub>–Al<sub>2</sub>O<sub>3</sub>–CaO–MgO–Cr<sub>2</sub>O<sub>3</sub> at  $P_{O_2} = 10^{-11.1}$  atm, Al<sub>2</sub>O<sub>3</sub> = 4.0 wt%, CaO = 0.2 wt%, and Cr<sub>2</sub>O<sub>3</sub> = 1.0 wt%.

- (iii) ISASMELT™ process for producing ferro-nickel alloys of various grades from nickel laterite ores.

Future development of the nickel ISASMELT™ process may require additional improvements to be made to the existing furnace designs. These include:

- Furnace cooling – operation at temperatures above 1300 °C will require furnace cooling systems to ensure sufficiently long campaign life;
- Tapping blocks – tapping of nickel matte/alloy will require improved tapping block design;
- Pneumatic injection – exploitation of dry concentrate injection through the ISASMELT™ lance to minimise fuel requirements; and
- Optimisation of the ISASMELT™ slag cleaning process to maximise payable metal recoveries.

These development issues are currently being addressed.

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