ESS Smelting Technology Enabling FeNi Smelting from Limonite

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Abstract

The RKEF process is widely used to produce ferronickel from saprolitic nickel ores. Limonites are mostly treated hydrometallurgically. However, limonites can be smelted in mini blast furnaces, in which case most of the iron is reduced with the nickel to produce nickel pig iron. Difficulties when smelting high iron limonite in an electric furnace are (a) controlled reduction of the iron and (b) in cases where the liquidus temperature of the slag is below that of the alloy, a high slag super heat to melt the alloy.

In ESS furnace technology, these problems are solved by performing solid state iron and nickel reduction in the top layer of the heap of feed materials and by heating alloy directly in a channel inductor to melt the heap from the bottom.

The ESS furnace design is rectangular with a large free board volume and three channel inductors mounted below the hearth. The raw materials are charged along one long sidewall of the furnace. The material is spread in thin layers over an inclined surface and heated by exposure to radiation from the free board. Conditions in the top layer of the heap permit solid state reduction.

Alloy in the bottom of the furnace flows into the channel inductor. Induction heats the alloy before it circulates to the over-flow trench against the other sidewall. The bottom of the pre-reduced heap is continuously melted by the heated alloy. The slag and alloy are at the same temperature and the operating temperature is determined by the highest liquidus temperature of either the slag or alloy.

The electrical energy consumption, smelting high iron limonite with 1.5% Ni in an ESS furnace, to produce a 15% FeNi alloy, is around 189 kWh/t limonite compared with 483 kWh/t limonite in an RKEF.

1 Introduction

Rotary kiln – electric furnace (RKEF) technology is widely used to smelt FeNi from saprolitic oxide ores. The ore and reductant are blended and calcined in the rotary kiln. The calcine is transferred at around 700°C to the AC electric arc furnace where it is smelted to produce a FeNi alloy. Successful operation of the furnace depends on maintaining suitable slag properties. Two important variables that are controlled during smelting are the SiO_2/MgO and Fe/Ni ratios in the feed blend.

Saprolitic ore is often covered by high iron containing limonite ore, normally with a lower nickel grade, a much higher Fe/Ni ratio and much less MgO. Limonites are mostly treated hydrometallurgically, but can be smelted into nickel pig iron (<15% Ni) in mini blast furnaces. The difficulty of smelting high iron limonite in a conventional RKEF process is to control iron reduction and, if the liquidus temperature of the slag is less than that of the alloy, the high slag superheat necessary to keep the alloy molten. One solution to overcome a low slag liquidus temperature is matte smelting, where the alloy liquidus temperature is lowered by the addition of sulphur.

In an ESS furnace, nickel and iron reduction takes place in the solid state. The alloy is not heated by the slag as in conventional AC furnace smelting, but directly in a channel inductor. A slag with a low liquidus temperature is heated with the minimum super heat needed to match the alloy temperature.

2 ESS furnace technology

The development of furnace technology utilizing channel inductors to melt iron, known as the IFCON process [1], started in the 1990's at Iscor in South Africa. Further development led to two prototype furnaces being built in India, but they are no longer operational. Sufficient operating data was generated to design the first commercial furnace, which is planned to be constructed in South Africa, to smelt a titaniferous magnetite into pig iron.

ESS smelting technology differs from other calcine-smelting processes in that it combines in a single furnace fossil fuel pre-heating and solid state pre-reduction of the oxide-containing feed materials with a minimum amount of electrical heating to produce molten alloy and slag [2]. ESS technology can smelt lumpy ores but is ideal for smelting fine raw materials directly, like limonites, exposing individual particles to radiation heating. The heap temperature is maintained by complete fossil fuel combustion. Reducing conditions at the operating temperature ensure solid state reduction in the top layer of the raw material heap. This is similar to reverberatory furnace operation. The additional energy to melt the reduced calcine is transferred from alloy heated in a channel inductor commonly used in the foundry industry to melt alloys. Efficient circulation of the alloy distributes the heated alloy from the channel inductor to the interface where the pre-reduced calcine is melted. The cooled alloy settles to the bottom of the furnace hearth before being heated in the inductors setting up controlled alloy circulation.

3 Furnace description

The furnace design is schematically shown in Figure 1. The furnace is rectangular. The raw material blend is charged continuously through multiple feed ports along one long wall of the furnace (the charge wall) to form a raw material heap. Combustion air and additional fuel are introduced through the opposite long wall (the melt wall). Complete combustion in the large free board volume improves heat transfer from the furnace gas to the raw material heap. The two off-gas ports are located in the opposite short walls, close the melt wall. The only area where liquid slag is in contact with the refractory is a narrow section against the melt wall. Copper coolers are installed in this area to maintain a freeze-line. The hearth of the furnace is designed to house the three channel inductors. The channel inductor throat passage is in the bottom of the hearth and smaller return passages open in an over-flow trench designed to facilitate even alloy distribution underneath the heap. The tap holes are located in the melt wall at the trench level above the channel inductors.

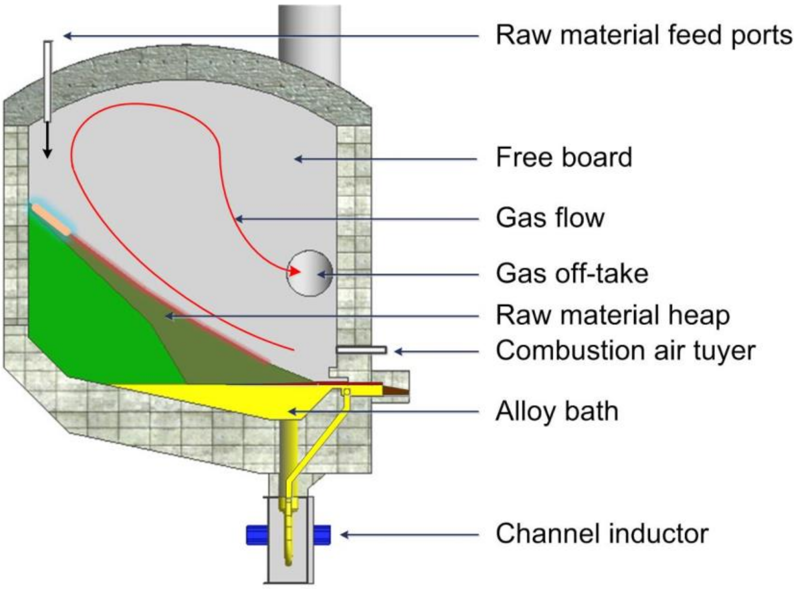

Figure 63: The ESS furnace

A small alloy pool is retained in the furnace. Colder alloy collects in the furnace hearth and flows down the throat of the channel inductor protecting the inductor from overheating. Efficient channel induction heats the alloy just enough to circulate it to the trench against the melt wall.

The bottom part of the reduced heap is continuously melted with heat from the alloy producing new molten alloy and a thin slag layer between the heap and the alloy pool. The slag accumulates over the trench. The slag and alloy are at the same temperature and the operating temperature is regulated by the highest liquidus temperature of either the slag or alloy. The channel design returns the heated alloy close to the tap hole simplifying slag and alloy tapping.

3.1. Furnace feed

The fine raw material blend consisting of ore and a reductant is mixed and micro-agglomerated to minimise dust losses during feeding. The optimum size of the micro-agglomerates is approximately 3mm. This blend is charged continuously through multiple feed ports along the charge wall. The large drop height ensures that the material is effectively spread in thin layers over the inclined heap surface. The angle of repose of the material determines the heap angle in the furnace.

Bridge forming is averted by preventing contact between the heap toe and the melt wall. Build-ups against the side walls are too far apart to form a strong continuous sintered layer. Moreover, the particles shrink during reduction making them less likely to form a strong sinter.

3.2. Solid state reduction

This raw material charging method exposes each micro-agglomerated particle to the process heat. This transfers radiant heat in the most efficient way to the individual particles before they are covered by the next layer. The atmosphere in the heap is reducing and at a high enough temperature (>900°C) to dry calcine and reduce nickel and iron oxides to metals. The degree of iron reduction is controlled by the amount of reductant in the feed blend.

Gas evolution from the reduction reactions limits diffusion of bulk gas in the free-board into the heap, preventing re-oxidation of the reduced nickel and iron. The low gas velocity in the free board minimizes dust entrainment. Maximum radiation heat transfer is ensured by the large heap surface area compared with the small liquid pool area.

3.3. Furnace freeboard

The primary energy source in the freeboard is CO gas emanating from the reaction layer. Depending on the energy balance, additional fuel (e.g. natural gas or pulverised coal) is injected. The combustion gas is pre-heated air, introduced through the melt wall, which is directed parallel to the inclined surface of the heap of material. The air can be oxygen enriched.

Complete combustion of the CO, volatile matter in the reductant and fuel is ensured by the cork screw circulating flow pattern of gasses in the freeboard. Excess oxygen in the free board gas is maintained to ensure complete combustion. The non-symmetric CO_2 and H_2O molecules in the gas ensure maximum heat radiation, unlike an EAF where the off-gas consists mainly of symmetrical CO molecules.

Energy is radiated from the gas and furnace roof to the heap surface. There will be areas where radiation is lower and active areas where it is higher. A value of around 120 kW/m^2 is assumed in the furnace design, but up to 180 kW/m^2 is reported in the laboratory experiments [3].

The Coãnda effect [4] enhances heat transfer to the heap as the combusted gas jet is drawn to and follows the upper surface of the heap. This ensures combustion close to the heap surface.

The roof and upper side walls are designed with no obstructions (feed and off-gas ports) specifically to ensure a large field of view, radiating energy to the heap surface. The fully combusted hot off gas at approximately 1300°C is extracted through the two end walls. Sensible heat in the off-gas is used to preheat the combustion air in an external heat exchanger.

3.4. The furnace hearth and channel inductor

The cooled alloy sinks to the bottom of the furnace where it enters the inductor through a large diameter inlet passage in the hearth, as shown in Figure 2. The alloy is heated by up to 30°C and through convective forces flows up the smaller diameter return passages. These passages open in a trench from where the heated alloy over-flows back into bath. At the top surface of the alloy, heat is transferred to the bottom of the heap melting it.

The slag and alloy are at the same temperature and the operating temperature is regulated by the highest liquidus temperature of either the slag or alloy. If the alloy has the highest liquidus temperature, it is at a temperature to maintain flow through the inductor. However, if the slag is at a higher temperature the alloy temperature will increase to a level where the slag melts, causing thermal arrest at that temperature.

The tap holes are at the trench level above the inductors. Slag accumulates over the trench against the melt wall before being tapped. Slag will be tapped almost continuously through two of the three tap holes.

At all times a relatively thin layer of slag is in the furnace, promoting alloy collection from the slag. At this interface, iron can reduce NiO in the slag further improving the nickel recovery and increasing the alloy grade.

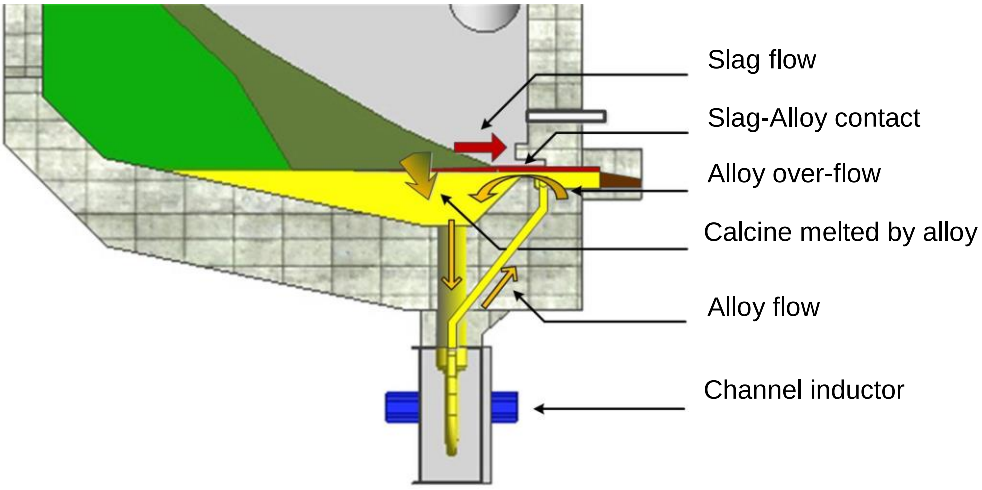

Figure 64: Furnace hearth and trench design

3.5. Energy balance

The large heap surface area compared with the small pool area promotes thermal energy transfer. The heap surface area is approximately 60m^2 and the area between the heap and alloy is 20m^2, a ratio of 3 to 1. At a heap heat transfer rate of 120 kW/m^2 approximately 7 MW is transferred to the heap and only 1.65 MW from the inductors (3 x 550 kW). Therefore, the ratio between thermal and electrical energy is approximately 5:1. There is currently no other technology that can achieve this level of electrical energy efficiency.

3.6. Start-up and shut down procedures

The channel former in the inductor is cast steel which is melted during the start-up. The cast steel melts above 1500°C which sinters the rammable refractory around it to form the channel. Once molten, iron is added from the top to create the molten metal bath and to fill the hearth to the desired level. Only then ore feeding does commence to create the heap above the hearth zone.

The inductors can only be switched off for very limited periods (5 to 10 minutes at a time) to prevent the alloy in the channel from freezing. The contraction of frozen alloy can result in damage to the channel refractory causing alloy penetrating when it is re-melted that leads ultimately to a run-out. A standby generator delivering around 10% of the full load (200 kW) must always be available in case of a power failure.

To empty the furnace, as much as possible of the material is tapped. A plug at the lowest point of the channel inductor is then removed to drain the alloy from the channels. The furnace must be fitted with a new inductor before it can be restarted.

4 Comparison with RKEF and blast furnace smelting

4.1. RKEF operation

An RKEF plant consists of a rotary kiln (RK) with an electric drive, a fuel burner and an off-gas handling system to capture dust entrained in the kiln gas. The thermal efficiency of a kiln is relatively low with limited pre-reduction. The hot calcine is transferred in a refractory lined transfer system, equipped with a dedicated crane, to refractory lined feed bins above the electric arc furnace (EAF). Dust generation and a decrease in the calcine temperature is unavoidable. The EAF requires a number of systems to operate well. Söderberg electrode management includes systems for casing and paste addition, paste level monitoring, electrode baking, hydraulic electrode movement and an advanced control system to control power input in the furnace. When operating an EAF with a covered arc, which is often the case in FeNi smelting, radiation from the bath to the furnace roof is significant, reducing the furnace thermal efficiency and often damaging the roof refractory. The furnace holds up to a meter thick layer of slag in contact with refractory requiring advanced refractory and freeze-line management. The furnace is tapped by first drilling the tap hole, often followed by oxygen lancing. This causes significant wear and tap blocks need to be replaced regularly.

In an electric furnace smelting limonite, the volumetric slag-to-alloy ratio is around 20:1 with at least a meter of slag on top of the alloy. Energy must be transferred through the slag to the alloy. Therefore, the physical properties of the slag are very important. The slag operating temperature must be higher than the alloy liquidus temperature to maintain a liquid alloy in the furnace. The alloy liquidus temperature depends on the nickel grade and carbon content, but generally is around 1500°C. It is clear from the phase diagram in Figure 3 [5] that the slag liquidus and tapping temperatures are above 1500°C. If the slag liquidus temperature is less than that of the alloy, the degree of slag superheat needed to ensure that the alloy in the furnace is molten, becomes prohibiting. PT Inco (point 7, now PT Vale) addresses this problem by smelting a matte with a lower liquidus temperature.

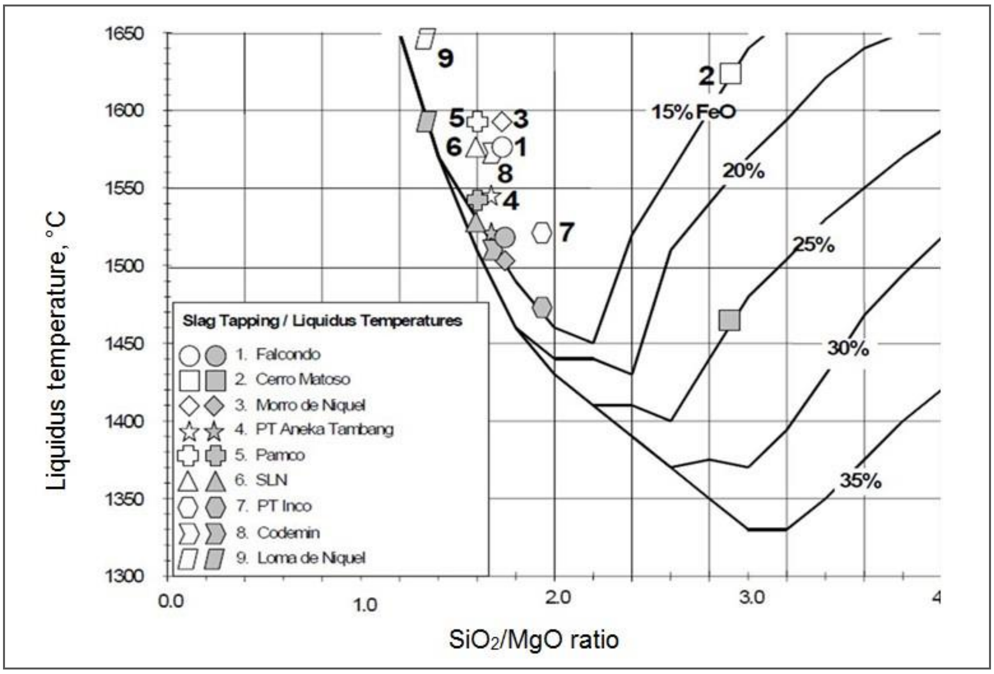

Figure 65: The system SiO_2-MgO-FeO

4.2. Mini blast furnace

Limonites are smelted in mini blast furnaces (M-BF). With the highly reducing condition in an M-BF most of the iron is reduced. At the Fe/Ni ratio of limonites, the nickel grade of the nickel pig iron (NPI) is typically less than 10%. While smelting the limonite the NPI grade will be around 4% (Table 1). Undesirable minor elements in the ore, e.g. S, P and Co, are also reduced and report in the alloy.

4.3. ESS furnace operation

An ESS plant requires less infrastructure as it is a single furnace with no moving parts. The feed system which consists of a high-intensity mixer and multiple screw feeders can be maintained without a furnace shut down. A single furnace for pre-heating, pre-reduction and smelting eliminates hot calcine handling. The higher calcine temperature combined with solid state reduction minimizes the electrical energy requirement. The hot slag and alloy in the furnace are close to the tap hole. Opening the tap hole does not require any drilling and lancing.

The alloy is melted directly making it possible to smelt limonite when the resulting slag liquidus temperature is less than that of the FeNi. The slag volume in the furnace is much lower, with most slag in close proximity of the alloy, minimizing alloy inclusions in the slag and driving metallothermic reduction of nickel oxide with iron. Slag in contact with refractory is limited to a narrow area which is much easier to manage.

The electrical energy efficiency of an ESS furnace is compared with that of the RKEF process in the next section.

5 Limonite smelting

5.1. Mass and energy balance

In this section, a typical mass and energy balance for smelting high iron limonite in an ESS furnace is compared with a hypothetical case smelting it in an RKEF. The limonite composition is shown in Table 1.

Table 1: Limonite and high volatile coal analyses

	Limonite
Ni	1.5%
Fe	43.7%
Al_2O_3	6.0%
MgO	1.5%
SiO_2	18.1%
LOI	10.0%
SiO_2/Al_2O_3	3.0
Fe/Ni	29.1

	Coal
FC	45.4%
Ash	6.6%
Volatiles	46.0%

The iron and nickel oxides in the calcine are reduced by carbon in the coal. As opposed to other smelting processes, high volatile coal is preferable with the volatiles being combusted in the free board, significantly contributing to the overall energy demand. High volatile coal is also more reactive which is an advantage in the ESS furnace. The same coal can be used as a fuel to supplement the freeboard energy requirement.

The rotary kiln in the RKEF process can also utilize higher volatile coals, but the associated higher reactivity of these coals increases the fixed carbon losses during combustion.

The liquidus temperatures of high iron slags are shown in Figure 4 as a function of the SiO_2/Al_2O_3 ratio. This is based on the iron rich corner of the SiO_2-Al_2O_3-FeO phase diagram. The CaO and MgO concentrations in the limonite are low and their impact on the liquidus temperature is not taken into account.

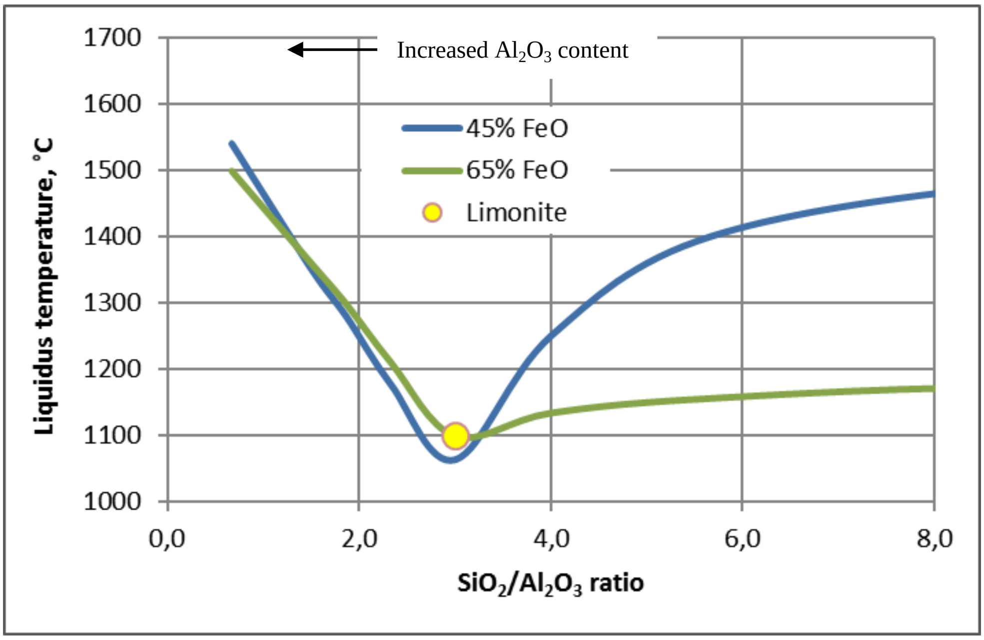

Figure 66: Liquidus temperature as the SiO_2/Al_2O_3 ratio increases

The SiO_2/Al_2O_3 ratio decreases as the alumina concentration increases. At a SiO_2/Al_2O_3 ratio of 3, the eutectic temperature is 1100°C. Once this ratio increases above 3, an increase in the iron content suppresses the liquidus temperature. The liquidus temperature of the slag smelting the limonite in Table 1 is at the eutectic temperature of 1100°C.

The ESS furnace is equipped with three 550 kW channel inductors. The mass and energy balance results shown in Tables 2 to 6 are at this electrical power input. An equivalent RKEF power of 4.5 MW was calculated to produce the same amount of nickel. In order to make the comparison more realistic, heat loss from the electric furnace was assumed as that from a 50 MW furnace.

The RKEF calculations are for comparison purposes only as the slag liquidus temperature smelting this limonite is too low and the iron content too high.

In the ESS furnace the feed blend is heated from room temperature above 1000°C on the heap. In the RKEF, calcine is transferred at a lower temperature (around 700°C) from the rotary kiln to the EAF. The slag and alloy temperatures in the ESS process are the same, whereas in an EAF the slag must be super-heated. FeNi smelting produces a large amount of slag, with slag super-heat contributing to an increase in the energy requirement in the EAF. Additional fuel is required in the ESS furnace free board. The amount of fuel is minimised by preheating the combustion gas with energy in the off-gas in a heat exchanger to at least 700°C.

Table 2: Operating temperatures

	ESS furnace	RKEF
Feed	25°C	25°C
Calcine	1 050°C	700°C
Free-board gas temperature	1 300°C	1 100°C
Alloy	1 500°C	1 530°C
Slag	1 500°C	1 600°C
Dust	800°C	800°C
Fuel temperature	25°C	
Combustion air to furnace	700°C	

The degree of the solid state reduction in the ESS furnace heap is compared to that in the kiln in Table 3. Iron and nickel reduction in the heap are controlled to produce the targeted FeNi grade. Solid state reactions in a kiln are limited by the operating conditions. Dust loss in the ESS furnace is limited, whereas in a kiln it is significant. Moreover, calcine transfer from the kiln to the EAF is a major operation with additional heat and dust losses.

In both ESS and RKEF furnaces, the final degree of reduction was assumed to be the same producing a 15% FeNi alloy.

Table 3: Furnace conditions

Solid state (thermal) reactions	ESS furnace	Kiln
Carbonate calcining	100.0%	100.0%
Fe_2O_3 to FeO	100.0%	80.0%
FeO to Fe	17.5%	0.0%
NiO to Ni	89.0%	10.0%
Final reduction	**ESS furnace**	**EAF**
Fe total	17.6%	17.6%
Ni	91.2%	91.2%
C	0.3%	0.3%
Si	0.07%	0.07%

The furnace free board conditions are summarised in Table 4. The heap temperature at 120 kW/m^2 thermal heating is 1050°C. The total energy transfer in the freeboard is 8.6 MW, including heat losses. Energy in the free board burning CO from reduction must be supplemented by burning pulverised coal. Other energy sources like natural gas can also be considered.

Table 4: ESS furnace freeboard

ESS furnace	Unit	Value
Thermal radiation	kW/m^2	120
Heap interface temperature	°C	1 050
Freeboard energy	MW	8.64
Fuel addition (Pulverised Coal)	tpa	7 726
	kg/t alloy	1 201
Combustion air	Nm^3/h	13 688
	Temp, °C	700

The limonite and reductant consumption, as well as alloy and slag production rates are summarised in Table 5. A single ESS furnace can produce 995 tpa nickel, smelting the limonite (Table 1). For smelting this limonite in a M-BF, the expected alloy grade is less than 4% nickel producing around 5 times more alloy to handle.

Electrical energy is used to heat the alloy in the channel inductor. This heat melts the calcine at the liquid-solid interface at the bottom of the heap into slag and alloy. The electrical energy requirement is summarised in Table 6 showing the specific (thermodynamic) energy requirement (SER) and specific energy consumption (SEC), the latter including furnace heat losses. The SEC of the RKEF process is calculated at 483 kWh/t limonite, which is approximately 50% of the total energy requirement. Smelting in the ESS furnace, the SEC is only 189 kWh/t limonite which is approximately 20% of the total requirement and 2.5 times less than that in the RKEF.

Table 5: Feed and products

	Unit	ESS furnace	RKEF
Total feed	tpa	80 546	86 963
Limonite	tpa	73 385	73 547
Reductant	tpa	7 160	13 416
Calcine Blend	tpa	59 807	65 970
Alloy production	tpa	6 632	6 632
Nickel production	tpa	995	995
Fe	%	84.6	84.6
Ni	%	15.0	15.0
Si	%	0.07	0.07
C	%	0.30	0.30
Slag	tpa	53 145	53 203
	t/t alloy	8.26	8.02
Al_2O_3	%	8.5	8.7
MgO	%	2.1	2.0
SiO_2	%	25.4	25.7
FeO	%	63.7	63.3
NiO	%	0.23	0.23
Fe	%	49.6	49.2
SiO_2/Al_2O_3	ratio	3.0	3.0
Ore-to-alloy ratio	t/t alloy	11.1	11.1
Slag-to-alloy ratio	t/t alloy	8.01	8.02

Table 6: Electrical energy requirement and consumption

	Unit	ESS furnace	RKEF
Furnace setpoint	MW	1.65	4.50
Utilisation	% per annum	96.0	92.2
Requirement (SER)	kWh/t limonite	166	403
	MWh/t Alloy	1.84	4.47
Consumption (SEC)	kWh/t limonite	189	483
	MWh/t Alloy	2.09	5.36

Smelting saprolite ore in an ESS furnace results in a similar improvement in the electrical energy consumption when compared with a RKEF furnace.

5.2. ESS furnace capacity smelting limonite

A 75 MW RKEF plant can produce around 18 000 tpa of nickel from the ore (Table 1). A single ESS furnace can produce 995 tpa of nickel. Therefore, a battery of 20 ESS furnaces will be required to reach those tonnages. With an estimated 50% capital cost saving per annual ton of nickel, and at approximately the same operating cost per ton nickel, clusters of these units are more economical. This is contrary to the normal furnace size trend in industry where larger units are more economical. The factors that drive the increase in furnace size are an incremental increase in thermal efficiency and a dilution of fixed cost per unit production. The ESS furnace delivers a step change increase in efficiency that cannot be matched by the largest RKEF.

Advantages of a modular approach are a lower initial capital requirement, building a single or a cluster of 5 furnaces for instance. The construction time is less when compared with a commercial RKEF plant, while earlier production of saleable alloy can support further staged expansion.

The furnace project can be located close to the mine where infrastructure like a power grid and process water is limited. The electrical power can be supplied using a small dedicated power system and closed circuit water is only needed for the inductor coils and copper coolers. Refining and granulation systems must be included.

A smaller ore deposit can support a furnace complex and the barrier to entry is less.

6 Conclusions

ESS smelting technology combines in a single furnace fossil fuel pre-heating and solid state reduction with a minimum amount of electrical heating to produce molten alloy and slag.

The electrical energy consumption smelting limonite in an ESS furnace is 189 kWh/t limonite, which is about 2.5 times less that in a RKEF.

High iron limonites are weathered and therefore are mostly fine. ESS is an applicable technology for smelting fine limonite directly.

The feed blend is charged continuously in thin layers over the inclined heap surface, exposing individual particles to the process heat. This ensures a maximum heap temperature and drives the required iron and nickel solid state reduction reactions.

The energy sources in the freeboard are completely combusted CO gas emanating from the reaction layer, volatile matter in the reductant and additional fuel.

Sensible heat in the hot off gas is used to preheat the combustion air.

Cooler alloy sinks to the bottom of the hearth. It enters the inductor through a large diameter inlet passage in the hearth where it is heated.

The heated alloy moves up the return passages into a trench from where it flows back into the alloy bath transferring energy to the solid-liquids interface in the furnace melting the calcine.

The tap hole is at the trench level above the inductor from where alloy and slag is tapped. This simplifies the tapping operation as drilling and lancing is not required.

ESS technology provides a very competitive opportunity to smelt limonite into FeNi. The only alternative is using mini-blast furnace technology but it produces low grade NPI.

7 References

[1] MANNING, C.P. AND FRUEHAN, R.J. “EMERGING TECHNOLOGIES FOR IRON AND STEELMAKING”, JOM, 53 (10) (2001), PP. 20-23.
[2] Fourie, L.J. and Erasmus, L.J. International Patent Application no PCT/IB2014/063629 Entitled “A Ferronickel Product and a Process for its Production”
[3] Coetsee, T. “Non-isothermal reactions of iron ore-coal mixtures”, Ph.D. dissertation, University of Pretoria, 2007.
[4] “The King’s Cross Fire” https://www.youtube.com/watch?v=Z_wpnuaM5Ig accessed on 24 January 2015.
[5] Voermann, N. Gerritsen, T. Candy, I. Stober, F. and Matyas, A. “Developments in Furnace Technology for Ferronickel Production”, Infacon X, 2004, pp. 455 - 465.