HIGH POWER, SHIELDED-ARC FeNi FURNACE OPERATION – CHALLENGES AND SOLUTIONS

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ABSTRACT

The productivity of FeNi smelting furnaces has risen steadily since the 1950's with an accompanying improvement in energy efficiency and reduction in capital and operating costs per pound of nickel produced. These increases have been enabled by the introduction of copper sidewall cooling technology and the shielded-arc smelting process in the 1970's and subsequent advances in furnace technology, control systems and operating practice.

Although there are substantial benefits to be realized from increasing productivity there are also challenges in achieving steady operation at high power and throughput. Lessons learned from recent furnace operating experience has improved understanding of the key issues with respect to maintaining process stability, feeding and tapping the furnace, controlling the molten bath temperatures and chemistry, maintaining crucible and roof integrity and delivering power reliably and efficiently to the furnace under high voltage arcing conditions.

These issues are analyzed and an understanding of the interaction between metal grade, calcine quality, power input per electrode, arc length and feed pattern on furnace operation and silicon reversion is presented using specific examples in context with their indirect effects on the crucible design and integrity. The effects of high power, arcing operation on power quality within the plant and on the power provider are also discussed.

Finally solutions for further productivity and efficiency improvements in the immediate future are proposed.

1 INTRODUCTION

The rotary-kiln electric furnace (RKEF) process has long been the most commonly employed means of recovering nickel from saprolitic laterite ores. While other technologies such as Xstrata's NST process are emerging, and blast furnace FeNi production has made somewhat of a comeback, much scope remains for increasing the productivity and efficiency of RKEF plants.

To achieve these improvements in production, the ferronickel industry has progressively increased furnace power levels over the years, as shown in Figure 1 [1][2]. This was achieved by a combination of several technological developments, most importantly the adoption of "shielded-arc" smelting (to replace the traditional immersed electrode mode of operation), and the installation of water-cooled copper cooling elements in the furnace sidewalls.

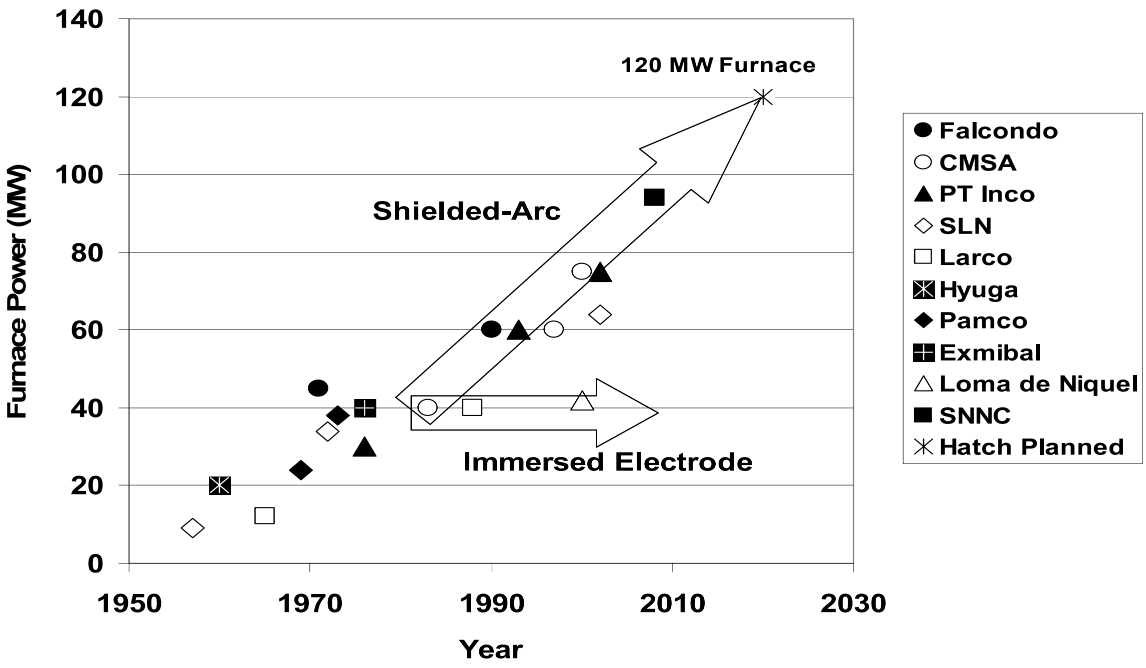

Figure 1: Evolution of furnace power over time

These technologies, pioneered by Hatch [3][4], have advanced to the point where one large kiln feeding 160 t/h of calcine to a single, 80 MW furnace can process approximately 1.3 million tonnes per year of new laterite ore. This has been well proven at PT Inco (Indonesia), Cerro Matoso (Colombia) and SNNC (South Korea), and is the standard for high power furnace operation. The motivation for the increase in power is substantial savings in both capital and operating cost per tonne of ore processed.

Of course the advantages of high power are only realized if the operating factor can be maintained and this requires a focus on the fundamentals of furnace design and operation.

Thus, in order to achieve success, particular attention must be paid to the following:

- Adequate measurement and control including:
  - Calcine feed rates
  - Calcine compositions
  - Furnace level measurements (hearth build-up, bath levels, calcine levels)
  - Metal and slag temperatures
  - Furnace crucible condition (temperatures, heat fluxes, brick thickness, expansion)
- Competent design of the crucible including:
  - Appropriate cooling
  - Appropriate expansion allowances and bindings
- Design and maintenance of feeding, offgas and metal/slag handling to ensure that upstream and downstream processes do not negatively affect furnace operating factor
- Careful selection of FeNi grade to be produced and corresponding selection of appropriate operating parameters.

2 HIGH POWER, LOW COST

The benefits of high capacity, reliable process units are illustrated in Table 1. Clearly a single furnace of 80 MW is more efficient and less costly to build than two 40 MW furnaces. Further improvements in efficiency and cost reductions can be achieved by making the vessel smaller and thus more intense (i.e., by increasing power per unit hearth area, known as power density). The net benefit of a small, intense (high power density) furnace relative to two equally sized, low intensity units (i.e., low power density) or even one large, high power but low intensity unit are illustrated in the table. Although small intense furnaces require robust copper cooling systems, the cost of the coolers are more than offset by the reduced cost of the total crucible due to a lower total tonnage of refractory and steel for the smaller furnace. Capital cost savings of up to $25 million dollars for the furnace alone (plus additional savings due to smaller buildings etc) can be realized by employing a high powered, intense furnace process.

Table 1: Benefits of High Power, High Intensity Furnaces

Parameter	Units	Current options for processing 1.3 Mtpy of dry ore compared to present "state of the art" 80 MW shielded-arc furnace			Furnace for 2 Mtpy of dry ore RKEF line
		Low Power	High Power, Low Intensity	High Power, High Intensity (State of the art)	Ultra High Power, High Intensity
No. of Furnaces		2	1	1	1
Furnace Power	MW	40	80	80	120
Calcine Production	t/h	159	161	166	250
	million t/y	1.18	1.20	1.24	1.86
Hearth Area	m2	225	450	225	350
Power Density	kW/m2	175	175	350	350
Total Surface Area	m2	1640	1420	820	1150
Thermal Losses	MW	8.4	7.6	4.9	6.8
Electrical Losses (Electrodes, LV Bus, Transformer)	MW	2.0	2.0	1.6	2.4
Total Losses	MW	10.4	9.6	6.5	9.2
Approx crucible(s) weight (refractory, steel, copper coolers)	tonnes	4500	4300	2400	3400
Furnace Installed Cost *	$ million	65	45	40	45
Capital cost per annual tonne of calcine smelted *	$/t calcine	55	38	32	24
Cost of energy loss **	$/ t calcine	$7.67	$7.00	$4.57	$4.33

** Furnace only (excludes offgas, feed system, utilities, building etc)*
*** Assuming a power cost of $0.10 / kWh*

Also, the greater surface area of larger low intensity units results in higher thermal losses and thus reduced efficiency. While there is a substantial increase in heat flux (energy loss per unit area) through the sidewall in the slag zone of an intense furnace, there are significant losses through the roof and bottom of a larger furnace, which more than offset the increase in the slag zone losses of the intense furnace. The roof and bottom heat losses vary only slightly when power density is increased and can be substantially controlled through proper feeding practice and by judicious choice of operating parameters, e.g., by using shielded-arc practice instead of immersed electrode, as discussed in following sections.

Additionally, if the high intensity is achieved through the use of shielded-arc smelting, the electrode current and thus electrical losses (which vary with current according to $P_{LOSS} = I^2R$) decrease for a high power density, shielded-arc furnace.

PT Inco gained a 33% production increase and reduction of heat loss by converting a furnace originally designed for immersed electrode operation to high intensity shielded arc operation [5]. For a new furnace designed specifically for high power shielded-arc operation, net reduction in heat losses of up to 30% relative to a large, low intensity furnace of equivalent power can be achieved (Table 2).

Table 2: Comparison of Heat Losses for Low Power Density and High Power Density Furnaces

Item	Large, low Intensity furnace (450 m^2 hearth area) 80 MW @ 175 kW/m^2		Small, high intensity furnace (230 m^2 hearth area) 80 MW @ 350 kW/m^2	
	Heat Flux (kW/m2)	**Total Loss (MW)**	**Heat Flux (kW/m2)**	**Total Loss (MW)**
Crucible Thermal Losses				
Bottom	2.3	1.0	2.3	0.5
Lower Wall	4.0	0.9	4.0	0.6
Slag Zone	12.5	0.9	25.0	1.3
Upper Wall	1.0	0.2	1.0	0.2
Roof	7.0	4.5	10.0	2.2
Subtotal Total Thermal Losses		*7.6*		*4.9*
Electrode and Electrical losses		2.0		1.6
TOTAL ENERGY LOSSES		**9.6**		**6.5**

3 CHALLENGES

The characteristics of high power density, shielded-arc operation in comparison to the traditional immersed electrode mode of operation have been described in detail by Voermann et al [2].

While shielded-arc operation has been successfully employed for over 35 years at operations including Falcondo, PT Inco and Cerro Matoso and is thus a well-established technology, as power levels continually increase and the range of ore characteristics widens, it is important to ensure that diligence is maintained.

The fundamental principles which lead to a successful high power, shielded-arc operation are:

- Ability to maintain an arc and manage the voltage and current fluctuations which are inherent in an arcing operation
- Ability to remove slag reliably from the furnace at higher rates than traditional operations
- Safe and reliable metal tapping operation
- Ability to feed the furnace reliably to maintain uniform charge cover in the relatively small smelting zone around the electrodes
- Ability to reliably contain the molten products in the crucible.

Each of these issues is discussed in more detail below.

3.1 Arc Stability

As a fundamental pre-requisite to successful shielded-arc smelting, an electric arc must be reliably maintained within a cavity under the electrode tip. An arc is inherently unstable and to maintain it requires that the electrode can be properly regulated and the calcine is fed in such a way that the arc is not snuffed by sudden introduction of large amounts of calcine in the arc cavities under the electrodes. Regulating a large Soderberg electrode column which can weigh in excess of 100 tonnes with reasonable accelerations (considering the building structure) still results in short term fluctuations in arc current and arc voltage of approximately +/- 20% around their set points. Fortunately there are more than one option for addressing these fluctuations, including advanced electrode controls [6] and, where required or beneficial, the installation of a variable reactance controller which can predict and adjust to voltage fluctuations in an arcing furnace [7]. The Smart Predictive Line Controller (SPLC) smoothes out the furnace power demand, and thereby delivers a higher average power (and hence enables higher calcine throughput), while reducing the peak power demand.

3.2 Slag Tapping

The area occupied by the molten bath (the active bath area) dictates the rate at which bath levels fluctuate between tapping operations. This is particularly important for slag, which has a lower density relative to metal and is produced at substantially higher rates. This makes a reliable tapping operation essential as there is reduced time before the slag level exceeds the maximum limits set by the crucible height and sidewall cooling system design. For an 80 MW furnace operating at a power density of 300 – 400 kW/m^2 (such as PT Inco) the slag rise rates can approach 200 – 300 mm/h (Figure 2).

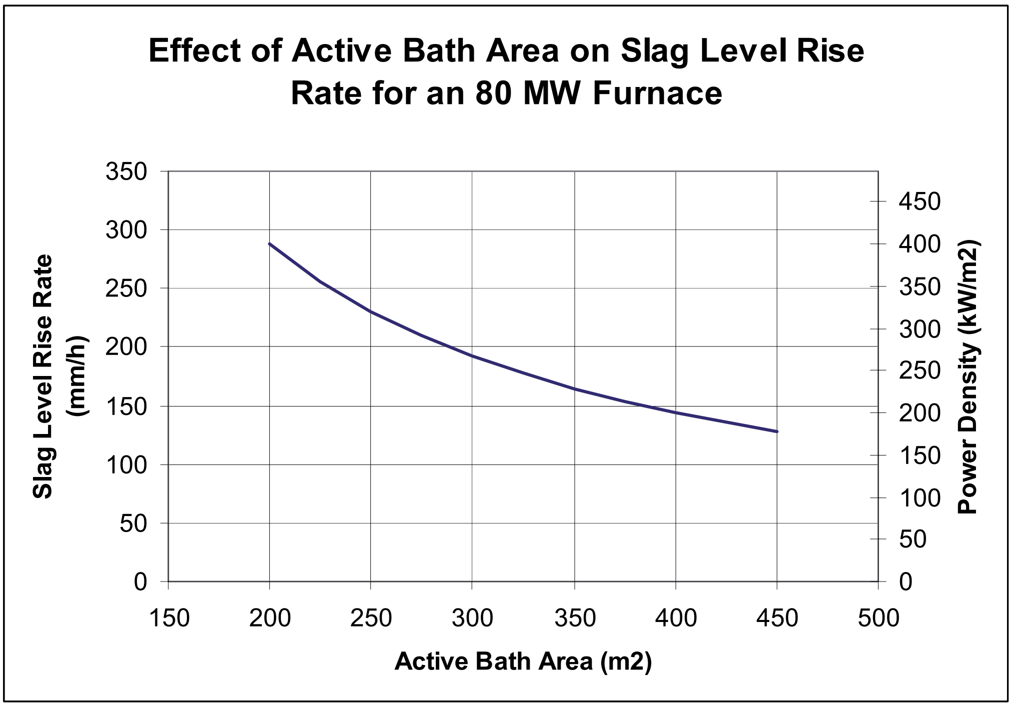

Figure 2: Effect of bath area on slag level rise rate for an 80 MW furnace

Nonetheless, slag tapping is not a major issue for most operations today. With a well-designed slag taphole and reliable granulation or tapping system, slag can consistently be tapped almost continuously from the furnace to prevent any interruption to operations from high slag levels. Cerro Matoso taps slag continuously for 22 hours per day from one of two tapholes, and rarely experiences interruptions due to slag tapping problems.

However, failure to maintain adequate level control can result in damage to the wall above the zone that is cooled, choking of the furnace freeboard and thus high gas temperatures, and/or splashing of the slag and damage to the roof.

Typically there is no more than 0.5 m of buffer capacity above the nominal slag level before the slag level exceeds the height of the cooled portion of the sidewall or the calcine banks reach the underside of the roof. This means that a 2 hour interruption in slag tapping leads to a power curtailment to contain slag levels below the maximum limit and thus a reliable slag handling process is essential to achieving a good furnace operating factor.

3.3 The Remaining Challenges

A significant consequence of high power, shielded-arc operation is the effects of the small, high temperature smelting craters in the centre of the furnace. The smelting zone comprises a high temperature, localized area directly below and adjacent to the electrodes. High power furnaces consume up to 90% of the calcine in the centre zone of the furnace (versus 60% or less consumed in this zone for immersed furnaces) and the reduction reactions occur at higher temperatures in the arc.

A direct result of a concentrated smelting zone is that:

- Most of the feed must be deposited into a relatively small area.
- As the gas produced from the smelting reactions must exit the smelting crater, a smaller area means an increase in velocity of the escaping gases.

- The high localized temperatures under the electrodes affect the reaction kinetics of certain elements which can have effects on process stability and metal superheat.

Before discussing these points individually it is important to understand the over-arching effect of FeNi grade.

3.3.1 Selection of Nickel Grade and Operating Mode

The amount of reduction that must be carried out in the furnace can have a large effect on the operation of a FeNi furnace and the overall economics of a smelter [8]. The extent of reduction required is a direct result of the iron to nickel ratio of the ore and the desired Ni grade of the FeNi produced.

The selection of Ni grade is thus an important determinant in the process characteristics and is therefore fundamental to the key issues in FeNi furnace operation.

In general producers of FeNi can be divided into two groups:

- Low reduction ("High grade") operations producing a Ni grade of 25 - 40% with iron recovery to metal in the 15 – 30% range
- High reduction ("Low grade") operations producing a Ni grade of 20 – 25 but with iron recovery to metal of 45 – 75%.

Note that the distinction between low and high reduction operation is dependant on the total amount of reduction (i.e. the amount of iron recovery to the metal) not solely on the nickel grade (i.e. some "low grade" producers may also be "low reduction" due to high Fe : Ni ratios in the ore).

From an economic standpoint, a variety of factors including the value of the iron contained in the product, transportation costs and energy costs are important in the selection of nickel grade. In very simple terms, low metal grade (i.e. high reduction) results in more of the iron in the calcine reporting to the furnace metal instead of to the slag, so superficially makes better use of the ore. However, low metal grade also means more of the energy input to the furnace is used to make iron rather than nickel, and hence diminishes nickel production compared to what could be achieved at the same furnace power level with higher metal grade. In addition, the cost to transport the iron contained in the FeNi to the market and the value of that iron to the market are important.

Metallurgical considerations are equally important in selecting nickel grade, although not always given due consideration. Foremost among these are:

- Performing a high degree of reduction in the furnace results in higher off-gas volume due to the extra carbon needed for the reduction reaction (FeO + C → Fe + CO). This increased off-gas generation affects not only the size and cost of the off-gas system, but also negatively affects arc stability and the ability to place feed completely around the arc cavity under the electrodes.
- The relatively high reduction usually needed to produce low metal grade also reduces silicon into the metal. This silicon can rapidly re-oxidise or "revert" from the metal to the slag. The consequent large energy release can be very detrimental to refractories at the slag-metal interface.
- The amount of reduction completed in the furnace has an important effect on the amount of carbon in the metal. Although the amount of carbon in the metal is somewhat dependant on the type, size and reactivity of the reductant used, high reduction operations typically have a metal with significant quantities of C and Si (~2%) whereas low reduction operations have an oxidized metal containing less than ~0.2% C. A significant result of this is that the carbon in the metal reduces the liquidus temperature of the metal. With the exception of operations processing ores with a low melting point, the tapping temperature of the metal in the furnace is typically set by the slag temperature, which in turn is chosen to be just hot enough to enable slag tapping. Thus, given a constant metal tapping temperature, higher reduction in the furnace and correspondingly higher carbon content of the metal generally means higher metal superheat. Metal superheat ranges from approximately 50 deg C for low reduction operations to more than 250 deg C for high reduction operations. For the latter, there are serious implications for tapping and containment of the metal bath that must be addressed in the furnace design and operation.

Therefore it is important to understand that the selection of nickel grade, furnace operation philosophy and furnace design are all inextricably linked and thus none can be truly optimised without consideration of the others.

3.3.2 Feeding and Gas Evolution

As previously discussed the largest impact of increasing smelting intensity through the use of shielded-arc operation, is the shrinking of the smelting crater within the furnace. This impact is schematically shown in Figure 3 below.

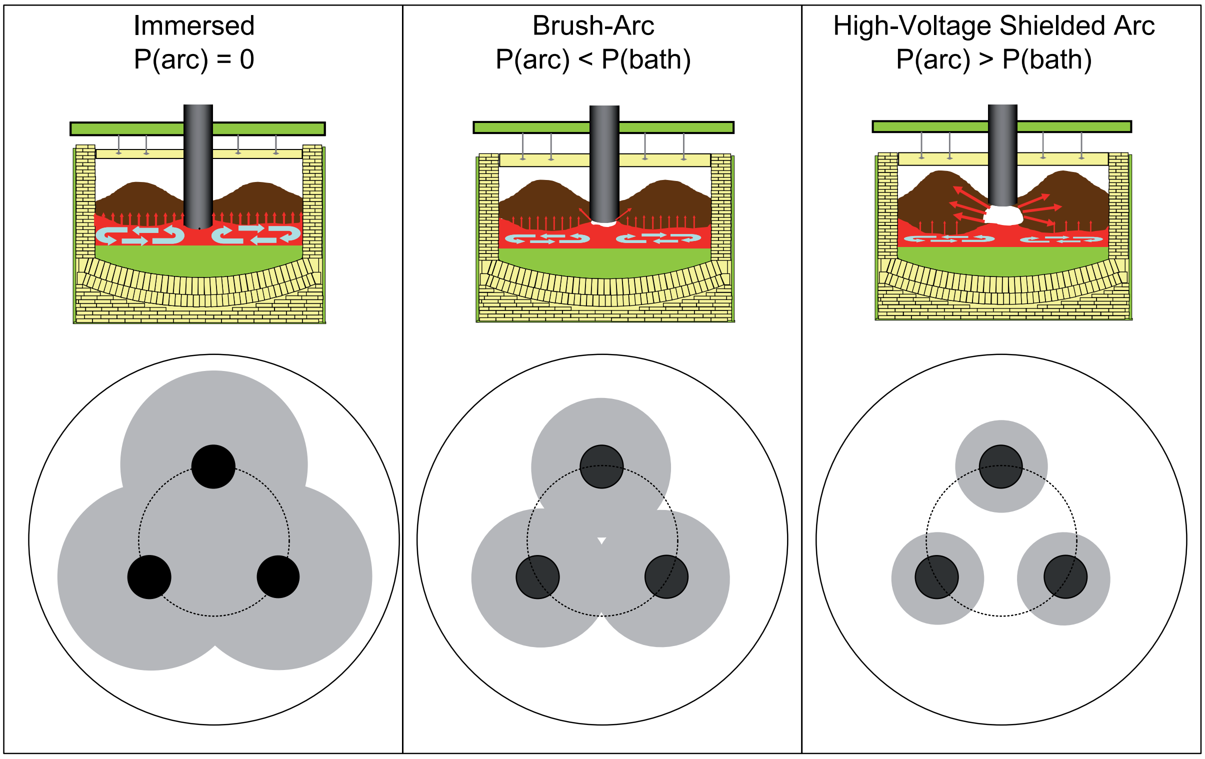

Figure 3: Smelting crater area representation for different furnace operating modes

The shaded area around the electrodes in Figure 3 represents the area in which the majority of the feed is consumed in immersed, brush (short) arc and high-voltage shielded-arc operation, respectively. It should be noted that the actual size of the smelting crater area is dependent on a number of parameters besides the furnace electrical operating mode. One of the most important of these parameters is slag composition and the slag liquidus and solidus temperatures, which can have a dramatic impact on the size and shape of the smelting crater in the smelting of ores of differing composition.

It is critical that calcine feed distribution to the furnace matches the feed consumption pattern resulting from the furnace operating mode. This is required to ensure that local areas of the furnace do not become devoid of calcine cover allowing for direct radiation from the slag and/or arc to the furnace roof; a leading cause of premature wear of roof refractories and excessive electrode consumption.

The following are required to successfully feed a furnace with a small smelting crater near the electrodes:

- Furnace roof layout, which accommodates the increased density of feed pipes needed to satisfy the calcine consumption profile, particularly in the area around the electrodes.
- Accurate, high-resolution measurement of the height of charge banks as they are consumed.
- Avoidance of process upsets (slag splashing, excessive foaming, etc.) which can cause charge sintering and restrict the calcine from flowing into the smelting crater.

A second problem that occurs with the shrinking smelting crater relates to the evolution of process gas from the charge banks. The volume of process gas exhausting from the top of the charge bank is a function of a number of factors including the degree of calcine reduction, calcine charge temperature and reductant (carbon) reactivity.

Charge gas is formed in the charge banks or at the slag / calcine interface by the general reaction:

$$M_xO_y + y\,C = x\,M + y\,CO \text{ (where M represents Fe, Ni, Cr, Si, etc.)}$$

Once formed in the charge banks, carbon monoxide gas migrates to the top of the charge bank where it is released to the freeboard. High gas velocities here can create significant problems by disrupting calcine flow and can fluidize or, in extreme cases, “blow out” calcine from the smelting crater immediately around the electrodes.

The total gas generation is governed mainly by power level and the amount of reduction carried out in the furnace (and hence, based on the discussion of Section 0, the ferronickel grade). Figure 4 illustrates the impact of FeNi grade on total process gas generation. It can be clearly seen that the FeNi grade or, more correctly, the amount of reduction required, has a large influence on the process gas generation. For this example there is a significant increase in process gas when moving from 35% Ni in FeNi to 20% Ni in FeNi and thus, all else being equal, the velocities in the smelting crater will also increase by a corresponding amount.

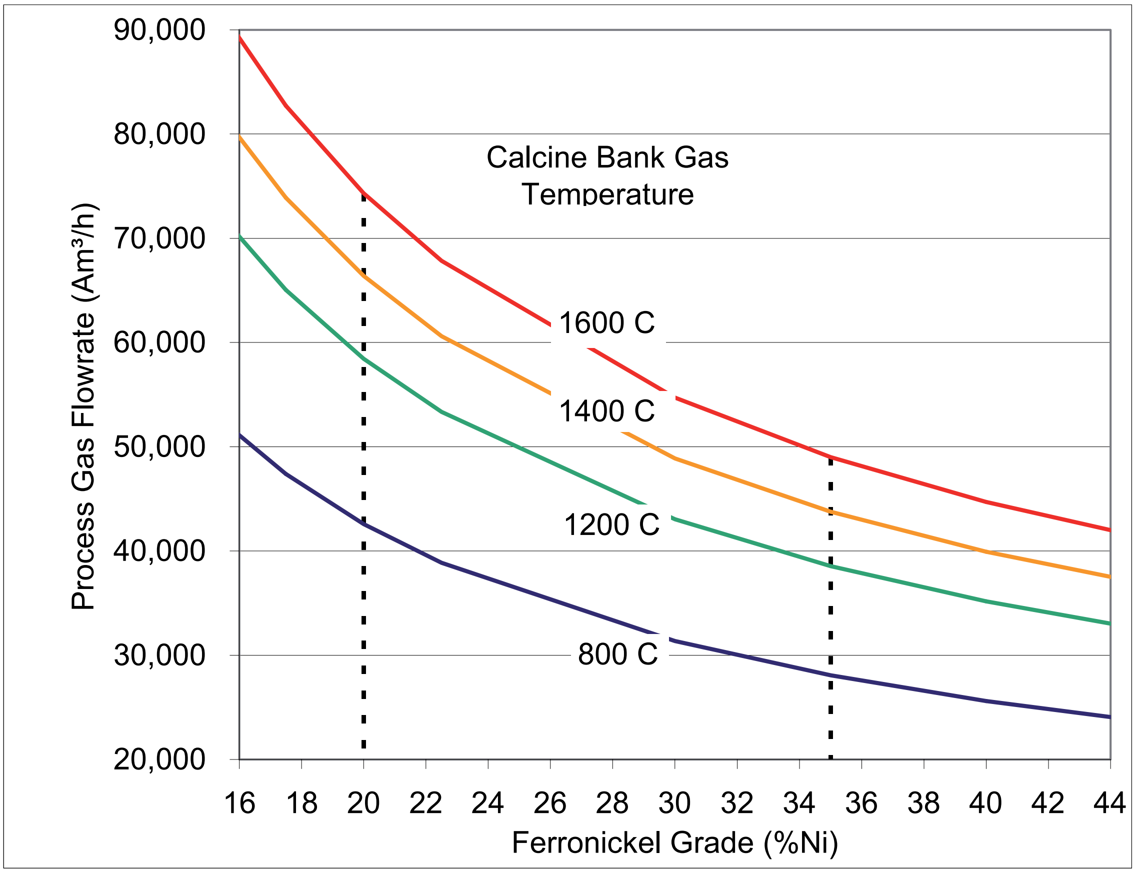

Figure 4: Example of the Impact of Ferronickel Grade on Actual Process Gas Flowrate

The gas distribution and thus localized velocity around the electrodes is further governed mainly by two factors:

- Operating mode (and corresponding arc to bath power ratio), which affects both the size of the smelting crater (Figure 3) and gas temperatures (and thus actual gas volume).
- Calcine feed pattern and calcine porosity. Sintering on the surface of calcine banks can also impact overall charge bank permeability, which tends to concentrate process gas evolution closer to the electrodes.

It is thus important to consider grade, feeding patterns, operating mode and calcine properties in designing and operating a high power furnace.

It should be noted that the higher average gas velocities that can accompany a shift from immersed to shielded-arc operation can be somewhat off-set by increasing ferronickel grade which reduces the total process gas volume. Thus, in addition to possible economic advantages, an increase in ferronickel grade from 20 to 35% and/or maximizing reduction in the kiln, can result in a significant reduction in average process gas velocity. This can help in achieving proper feeding and reduce the incident of burners and gas jest impinging the roof and causing severe wear.

Challenges associated with meeting the calcine smelting profile in the furnace and managing high process gas velocities can also be reduced using a rectangular six-inline furnace design as opposed to a three-in-delta round geometry, for the following reasons:

- For a given power level the power per electrode in a six-inline furnace is half that for a three-electrode-circular furnace and hence, for similar arc to bath power ratios, the active smelting crater area is significantly larger for a rectangular furnace.
- Available roof designs (e.g., sprung arch) for the rectangular furnace allow for less congestion in the area of the electrodes and hence better positioning of calcine feed pipes is possible.

3.3.3 Process Stability: Silicon Reversions

A process upset known as “silicon reversion” occurs when silicon in the metal bath is re-oxidised and “reverts” to the slag bath. This reversion process is very exothermic, and hence results in a large release of energy at the slag / metal interface that can be detrimental to the furnace lining in this area. Based on recent experience it has been well established that these silicon reversions occur almost exclusively in furnaces where high levels of reduction are occurring and that these events are more likely to occur when operating in the arcing mode.

The reduction of SiO_2 to silicon metal relies on sufficient excess carbon in the calcine and relatively high temperature to promote the reduction reaction:

$$C + \frac{1}{2} SiO_2(s) = \frac{1}{2} \underline{Si}_{FeNi} + CO(g)$$

With high temperature and accumulation of carbon in the smelting crater of a furnace operating in the shielded-arc mode, Si can approach its saturation level in the metal prills formed in the arc cavity (where temperatures are substantially higher than the bulk slag temperature).

As the saturation limit for Si in the prills increases with temperature, this may allow for the formation of prills in the arc cavity with Si levels in excess of that thermodynamically possible for prills at the average slag temperature. These super- saturated prills could either:

- React with available oxides in the bulk slag as the prills settle thereby heating the prills as they settle thereby adding heat to the metal bath and reducing the differential between the slag and metal temperature, e.g.,

$$.\ \underline{Si}_{FeNi} + 2(FeO) = 2\underline{Fe}_{FeNi} + (SiO_2) \qquad H_{1550°C} = -3.08 \text{ kWh/kg Si}$$

- Or fail to react owing to mass transfer or other hindrances and deliver high levels of Si metal to the ferronickel.

Both of these cases pose substantial risks to operation by leading to highly superheated metal bath. The intermittent nature of Si reversions which occur with the latter of the two options for supersaturated prills can generate large inventories of silicon in the metal as a form of stored chemical energy and hence can pose the very serious risk to ferronickel furnace operations if this energy is rapidly released in a silicon reversion.

It should be noted that silicon reversions are generally initiated through changes in carbon content of the metal prills reaching the metal bath (due to variation of carbon in calcine) or changes in temperature which affects the equilibrium. Once started, the resulting reaction proceeds unchecked until a new equilibrium is reached with an immense release of energy.

Recent operations have witnessed silicon reversion which lasted for 1 or 2 days and resulted in a drop of Si content in metal of 4% or more. The release of energy has been observed to raise the metal temperature by up to 100 deg C [9] even with a curtailment of power during the event.

Such events can disrupt operations significantly through lost production as power is curtailed to control temperatures and through increased risk of damage to the furnace lining from thermal cycling and highly superheated, low viscosity metal penetrating the lining.

The existence of the silicon reversion phenomenon in high power intensity furnaces favours operation at low degree of reduction (i.e. high ferronickel grade) within the furnace to avoid the thermodynamic conditions at which silicon metal can be formed.

3.3.4 Crucible Integrity: Molten Bath Containment and Metal Tapping

As operations rely on more powerful but relatively fewer furnaces, the integrity of the crucible becomes increasingly more important.

The cooling of furnace sidewalls in the slag zone using water-cooled elements is well known and proven. Even with highly superheated slag and power densities of 400 kW/m^2 or greater, the existing Hatch technology can easily provide sufficient cooling to protect the lining in this area. Typical slag zone heat fluxes in the FeNi industry range from averages of 10 – 50 kW/m^2 with peaks of up to 100 kW/m^2. Heat fluxes at the top of this range are handled easily by deep-cooled copper plate coolers [10]. Slag zone run-outs are relatively rare in modern FeNi furnaces.

Far more challenging is containment of the molten bath in the slag/metal interface zone. Here the wall is contacted by both slag and metal alternately as the metal level rises and falls. The heat fluxes on a furnace wall in this area can be 100 – 200 kW/m^2 which in the case of a refractory only wall results in an equilibrium residual refractory / frozen slag build-up thickness totalling only 25 mm. In such case there is very little protection between the metal bath and the shell. Small cracks in the remaining brick or spalling of the frozen slag layer can lead to run outs. The problem becomes more severe if the metal temperature exceeds the slag liquidus temperature as any protective layer of slag can be melted off by rising metal.

One solution to the interface zone wear is to insert a robust heavily water-cooled copper block such as a Hatch Waffle Cooler. This serves as a barricade against the metal wear and was implemented at Cerro Matoso (Figure 5), where it has successfully contained the process on Furnace 2 since 2000, and will soon be implemented on Furnace 1 there. However placing a water-cooled copper block in an area where contact with metal is a possibility carries a certain amount of risk. Even a well-cooled copper block has a finite ability to withstand hits from highly superheated metal.

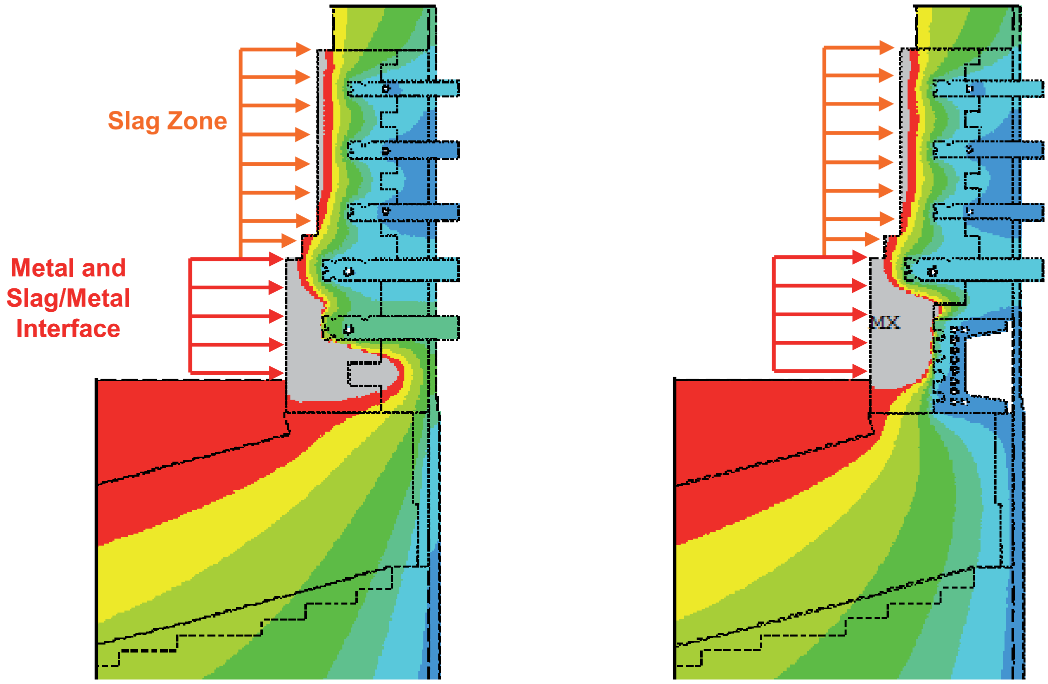

Figure 5: Slag/Metal interface zone erosion and solution at Cerro Matoso

The equilibrium heat flux for metal bath in contact with a cooler can be expressed by:

$$\left.\frac{Q}{A}\right|_{WALL} = h_{Metal}\left(T_{M\ bulk} - T_{M\ MP}\right) = h_{Metal}\ \Delta T_{Superheat}$$

The metal bath heat transfer coefficient is difficult to assess with any certainty but Chiesa and Guthrie have derived the following relationship [11]:

$$h_{Metal} = 0.11(k\rho)^{2/3}\left(\frac{\beta g C_p \Delta T_{Superheat}}{\mu}\right)^{1/3}$$

Where,

k	=	thermal conductivity of metal
ρ	=	density of metal
β	=	coefficient of volumetric expansion
C_p	=	specific heat of metal
μ	=	viscosity of metal

Thus,

$$\left.\frac{Q}{A}\right|_{WALL} = 0.11(k\rho)^{2/3}\left(\frac{\beta g C_p}{\mu}\right)^{1/3}\left(\Delta T_{Superheat}\right)^{4/3}$$

The equation above shows that the heat flux from the metal bath to the hot face of a copper cooler is very dependant on the metal bath superheat. This relationship is plotted graphically in Figure 6. It is noteworthy that estimated heat flux increases by an order of magnitude as metal superheat increases from 40 degree Celsius (typical of a high grade, low C FeNi production) to 250 degrees Celsius which can occur in furnaces producing a low grade FeNi metal with high carbon content (i.e. metal with a low melting point).

Although Figure 6 is an approximation it serves to provide a reasonable estimate of the heat fluxes to which a copper cooler can be subjected when contacted directly by highly superheated metal. It correlates reasonably well with measurements of cooler heat load during known events where molten metal has come in contact with Hatch Waffle Coolers (although it slightly under predicts measured values). Note that the equation assumes that the metal is frozen on the hot face of the cooler. If metal finds an outlet and continues flowing past a cooler, the heat fluxes may be substantially higher.

The ability of a robustly cooled solid copper block to withstand heat fluxes of 3000 – 6000 kW/m^2 which can be expected for a high reduction (high metal superheat) operation depends on the area of exposure to direct contact with liquid metal. Hence, the waffle pattern on the hot face of the Hatch Waffle coolers is designed specifically to limit this contact area. Even so, recent incidents on both FeNi furnaces with metal superheats of approximately 200 deg C and platinum group metals (PGM) smelting furnaces where superheat can be above 500 deg C, indicate that the area of copper that can be directly exposed to highly superheated metal (> 100 deg C) is quite small. When metal finds a path and can continue to flow past a cooler there is little chance that the cooler will survive. For this reason, in operations where high metal superheats are present, the solution for the slag metal interface zone employed at Cerro Matoso is not recommended.

It is thus of paramount importance, particularly in high reduction operations, to avoid placement of the coolers in the metal zone except where necessary and to ensure that the refractory in front of the coolers remains in tact. Additionally, good control of metal bath levels is required to minimize the risk of metal contacting coolers placed in the slag zone.

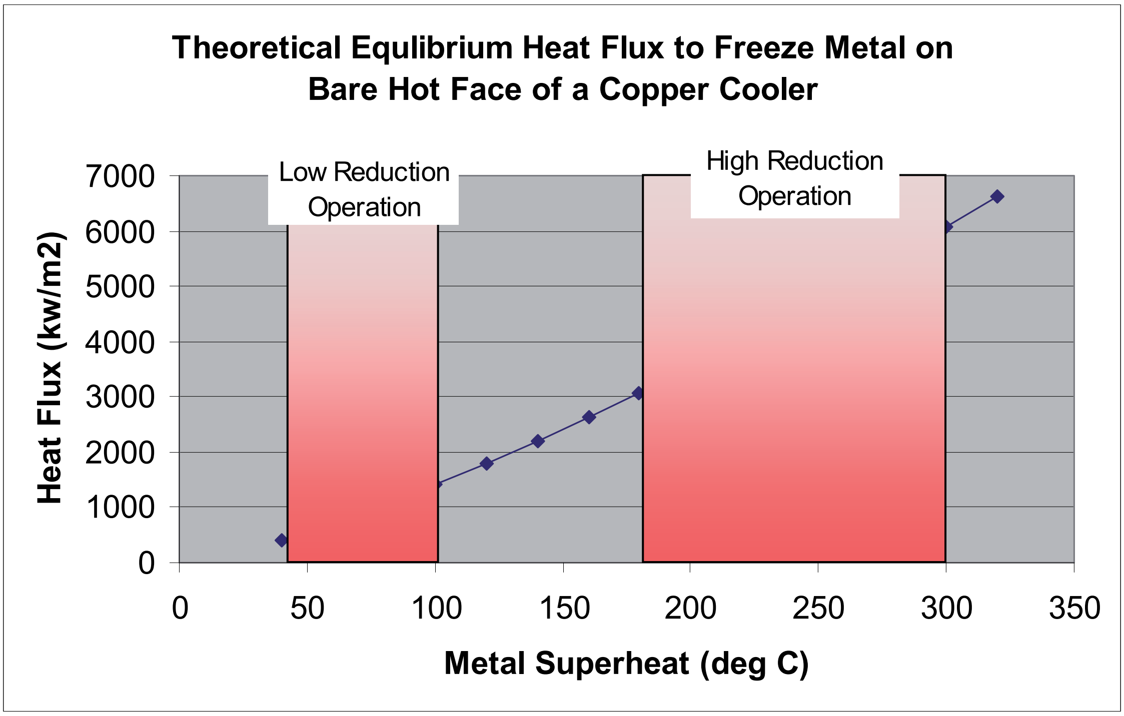

Figure 6: Effect of metal superheat on copper cooler equilibrium heat flux (with no refractory protection)

Water-cooled metal tapholes are known to provide many advantages, hence the ability to monitor refractory wear and replace worn bricks to effectively manage the risks outlined above are an inherent part of modern tapblock technology. The importance of proper monitoring and maintenance of coolers in the metal zone cannot be understated. Fortunately, this process is now being facilitated by advances in technology outlined below.

3.3.5 Advances in Cooler and Tapblock Monitoring

For highly superheated metal, the monitoring of tapblocks and coolers in the slag/metal interface zone is particularly important. Traditional monitoring systems are comprised of cooling water temperature monitoring systems and discrete thermocouples placed near the hot face of the block. Recent events with metal contact have exposed the limitations of these methods. In some cases where copper coolers or tapblocks have been damaged by contact with highly superheated metal, the monitoring instruments have provided little or no warning and, in a few instances, the temperature readings, although elevated, remained below alarm limits. The reason for this is clear if one considers the macro effect of even a small metal contact on the overall heat load to a cooler. Figure 7 shows the effect of the area of cooler subject to contact with highly superheated metal on the overall cooler heat load and cooling water temperature rise. It is interesting to note that for the example shown, metal must contact the cooler over an area of at least 70 cm^2 on a 500 cm^2 cooler (i.e. 15% of the total area) before an alarm limit is reached (in this case set for twice the expected, average heat load).

Similarly, discrete thermocouples mounted at the hot face can be “shielded” from a metal contact either by distance from the contact point or by a cooling passage between the thermocouple and the area contacted by metal.

In order to improve the safety of tapblock and coolers where there is a risk of contact with metal a two-pronged approach is needed:

- The refractory in front of these coolers must be maintained intact;
- A means of detecting temperatures across the entire hot face is needed.

To address the first point, monitoring the condition of refractory is a key component and this can be done by monitoring of temperatures and thermal analysis to determine remaining brick thickness. Acoustic measurements are also a method of measuring refractory condition in front of coolers and in the tapping channel of tapblocks [12].

For improved temperature monitoring, fibre optic temperature systems have been introduced. These systems facilitate monitoring of hundreds of points on the hot face of the block, compared to the 6 to 12 points in the tapblock traditionally monitored by thermocouples. The mesh of measuring points enabled by using fibre optic temperature sensing provides early indication of problems. A fibre optic system has successfully been implemented at Lonmin Platinum in South Africa with demonstrated greater resolution than available from traditional thermocouple systems. This fibre optic system enables much earlier detection of protective refractory wear problems, and is now commercialized [13].

In combination with improved monitoring, design to allow access for easy replacement of taphole refractories is essential. A diligent monitoring and preventive maintenance program is crucial for any cooling element that can be contacted by highly superheated metal. These are key features of modern tapblocks but are more difficult to implement in an entire ring of coolers located in the metal or slag/metal interface zone of a furnace producing low grade ferronickel (i.e, high reduction operation) where metal superheats can be excessive.

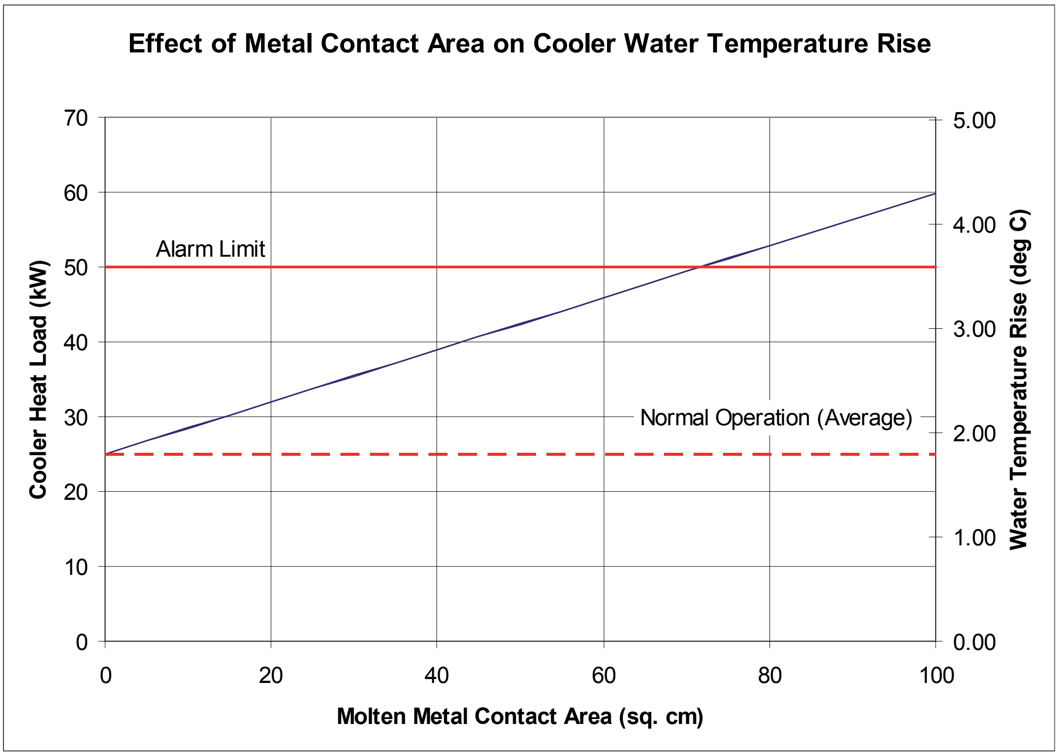

Figure 7: Effect of metal contact area on cooling water temperature rise.(Assuming 3500 kW/m2 at metal contact on a cooler with 200 lpm of cooling water)

3.3.6 Bindings and Expansion

In addition to adequate cooling, a fundamental element of containment of the metal bath is the accommodation of expansion of the various components, which make up the furnace lining. Differential expansion between hot bricks and relatively cool copper elements as well as gaps created through thermal cycling can all lead to a reduction in integrity. Placement of the copper coolers and integration with the surrounding bricks as well as application of suitable three-dimensional (3D) binding forces on the lining are all fundamental to the maintenance of a robust lining.

It should also be noted that a key component of maintaining a robust refractory lining is a careful initial start-up procedure [14]. More than one furnace has been damaged irreparably by an overly aggressive or poorly planned start-up. Metal penetration into wall or hearth bricks during start-up will lead to events much later especially if a carbon boil or Si reversion combines to increase metal temperatures.

3.3.7 Roof Wear

Excessive roof wear is a prevalent issue on many FeNi furnaces. The cause of the wear can vary but often can be attributed to:

- Excessive freeboard temperatures from uncovered bath or uncontrolled freeboard combustion
- Slag splashing from foamy slag, open bath or high bath levels
- CO gas jets from the central smelting zone

Most FeNi operators are wary of installing water cooled roofs and have focused instead on improving access and maintainability. In future, consideration needs to be given addressing the root causes. Once again the selections of process parameters (FeNi grade and operating mode) as well as design of the feed system to provide adequate bath cover are key to minimizing roof wear issues. A key component of maintaining adequate feed cover is the measurement of feed composition, weights and calcine bank heights. Monitoring freeboard and roof temperatures is also an effective means of detecting hot spots early to enable planning and prioritization of maintenance.

4 HIGH POWER FURNACE FOR THE FUTURE

As power levels increase furnace designers and operators need to turn their attention toward better monitoring and control. While incremental improvements in cooling, binding and refractory design will continue, improvements to the robustness of these systems are approaching the point of diminishing returns. Huge gains have been made in these areas, as reflected in today's state of the art Hatch furnaces. However further gains will rely on the ability to monitor conditions in and around the furnace and fine tune parameters which effect not only the process but also the integrity of the equipment.

Given the issues outlined above, to further increase furnace power and throughput, and to thereby reap the substantial benefits still available from the economies of scale, furnace designers and operators must:

- Select the process parameters with a full understanding of metallurgical, economic and equipment integrity issues. This includes an appropriate selection of metal grade and suitable operating mode.
- Use available furnace technologies to maximize scale, and thereby minimize capital cost and operating cost per unit of FeNi production,
- Implement procedures for careful sampling and weighing of calcine as it goes into the furnace. It is vitally important to know how much calcine is going into the furnace and where it is being fed, particularly when operating at intense smelting rates. A well designed and controlled feeding system must:
  - Avoid hot spots and minimize segregation that can lead to gas jets
  - Deliver feed consistently to where it is needed, when it is needed
  - Maintain a consistent quality of feed (measure and adjust LOI and C) by sampling calcine at the furnace and providing a direct feed back to the kiln operation
- Design, start-up, operate and maintain furnaces to accommodate thermal expansion:
  - Adequate bindings
  - Appropriate expansion allowances and attention to the differential expansion between the many components of which the lining is comprised
  - Start-up shut down and operation procedures that are based on fundamentals of maintaining crucible integrity
- Pay due attention to design, operation and maintenance of auxiliary systems (eg slag tapping, offgas and power supply) to ensure that the furnace operation is not hindered due to indirect effects upstream and downstream
- Improve the monitoring of the furnace condition which includes;
  - Bath and feed level monitoring and control
  - Refractory and cooler condition monitoring through implementation of emerging non-destructive technologies such as fibreoptic temperature measurement and acoustic monitoring.

The technology for major advances in furnace productivity, and hence lower capital and operating costs per unit of nickel produced, is available and proven [15]. With an understanding of the issues outlined in this paper, and appropriate adoption of these technologies, the implementation of further power increases to 120 MW and beyond are achievable with minimal technical risk.

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