DEVELOPMENTS IN FURNACE TECHNOLOGY FOR FERRO-NICKEL PRODUCTION

N. Voermann, T. Gerritsen, I. Candy, F. Stober and A. Matyas

HATCH, 2800 Speakman Drive, Mississauga, Ontario Canada L5K 2R7.
E-mail: nvoermann@hatch.ca, tgerritsen@hatch.ca, icandy@hatch.ca, fstober@hatch.ca and amatyas@hatch.ca

ABSTRACT

This paper describes developments in ferro-nickel furnace technology, specifically improvements to cooling methods, furnace controls, and high voltage furnace operating regime. The evolution of these technologies is briefly presented, as context for describing the current state of the art that has enabled ferro-nickel furnace operation at over 75 MW and specific energy consumption of less than 400 kWh/t dry ore. Examples from existing operations are used to illustrate present best practices, and potential future trends are discussed.

The paper begins with an overview of the fundamental aspects of pyrometallurgical treatment of lateritic ores that drive ferro-nickel furnace design. Furnace wall cooling methods are related to the requirements resulting from specific furnace process conditions, including slag and metal compositions, as well as arc and bath power. The benefits of high productivity and low specific energy consumption resulting from high voltage (shielded-arc) operating practice are discussed, along with the furnace controls and electrical power train that enable such operation even with captive power generation.

1. INTRODUCTION

The trend toward high-power high-productivity electric furnaces for nickel laterite smelting has continued to advance. Figure 1 shows the progressive increase in furnace operating power levels over the years. The new electric furnace installed at Cerro Matoso (Colombia) now operates routinely at 75 MW.

Many early ferro-nickel producers operating at moderate furnace power and on ore with favourable SiO_2/MgO ratio have been able to do so successfully with relatively simple furnace technology (similar to that used for submerged arc furnaces). This is possible because of the low superheat of both the ferro-nickel metal and the slag in these cases. However, increased furnace power and power density, and/or use of ores with less favourable SiO_2/MgO ratio resulting in high superheats, necessitates the application of newer technologies to maintain furnace integrity. The major benefit of high power furnaces is high single line capacity, resulting in lower CAPEX per annual tonne, and lower energy, electrode and labour cost per tonne for one large furnace compared to a number of smaller furnaces.

The implementation of high-power ferro-nickel furnaces has been made possible by the following key technical and engineering developments:

- Application of high voltage to provide a shielded-arc under the electrode tip which enables transferring high power loads directly to the calcine charge
- Installation of penetrative water-cooled copper elements in the furnace sidewalls and robust binding systems that provide long furnace life under intense smelting conditions.
- Use of sophisticated and integrated furnace controls and power supply trains to manage high power levels under arcing conditions.

The successful development of these technologies has required a multi-disciplinary approach combining the various metallurgical, thermal, structural, electrical, and controls components. Some of these designs were first developed for ferro-nickel furnaces, while others were adapted from matte smelting furnaces. This paper describes the origins and underlying technical considerations of each of these elements, and their integrated application to ferro-nickel furnaces, as well as future trends and developments.

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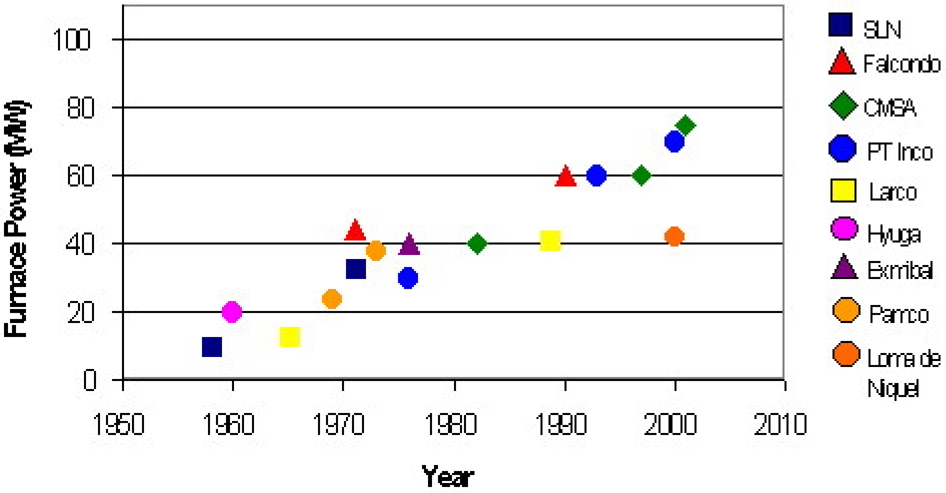

Figure 1. Ferro-nickel furnace operating power vs. year of original start-up or major upgrade.

2. METALLURGICAL ASPECTS OF FERRO-NICKEL FURNACE DESIGN

Furnace design and particularly the cooling system design, depend fundamentally on the process metallurgy.

The required metal temperature for tapping is typically about 25°C above the metal liquidus. The liquidus, a function of the chosen ferro-nickel grade, is in turn determined by the degree of calcine reduction. This is illustrated in Figure 2, which plots metal liquidus temperature, nickel grade and carbon content for a number of ferro-nickel operations. The temperature of the metal actually tapped from a furnace depends primarily on the slag temperature (although metal fall, hearth conductivity, slag layer thickness and viscosity, as well as other factors are also significant).

Therefore, the minimum slag temperature required is set by:

- metal temperature criteria for metal tapping as outlined above, and/or
- the usual requirement for a slag tap temperature at least 50°C above the slag liquidus to ensure sufficient slag fluidity for good metal/slag separation and slag tapping.

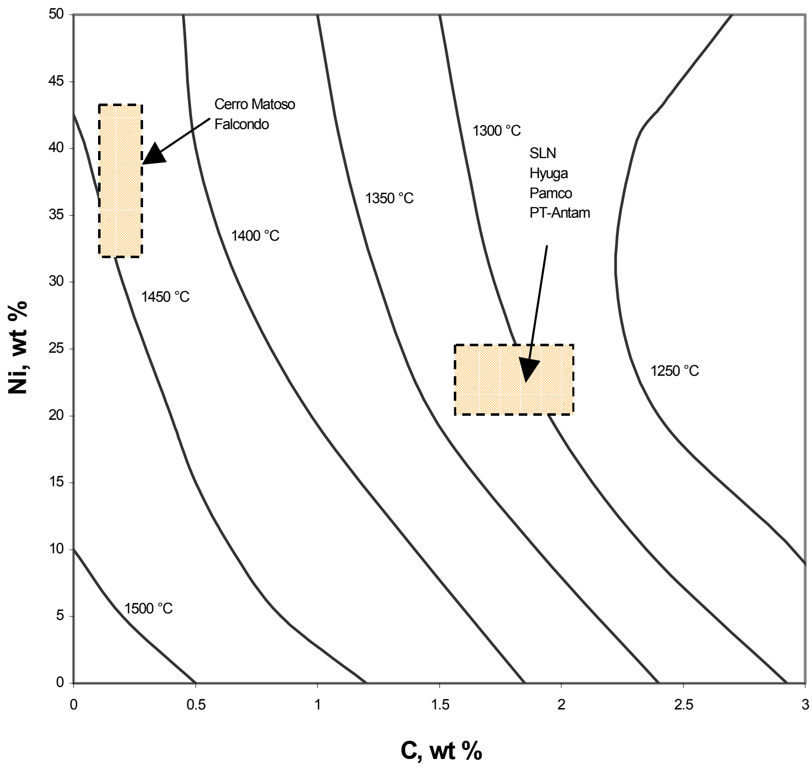

Figure 2. Liquidus temperatures for C-Fe-Ni System [1].

Figure 3 illustrates slag liquidus and tapping temperatures for a range of slag SiO_2/MgO (S/M) ratios and slag FeO contents. It will be noted that the slag tapping temperature minus its liquidus temperature, or slag superheat, varies substantially between the specific examples indicated.

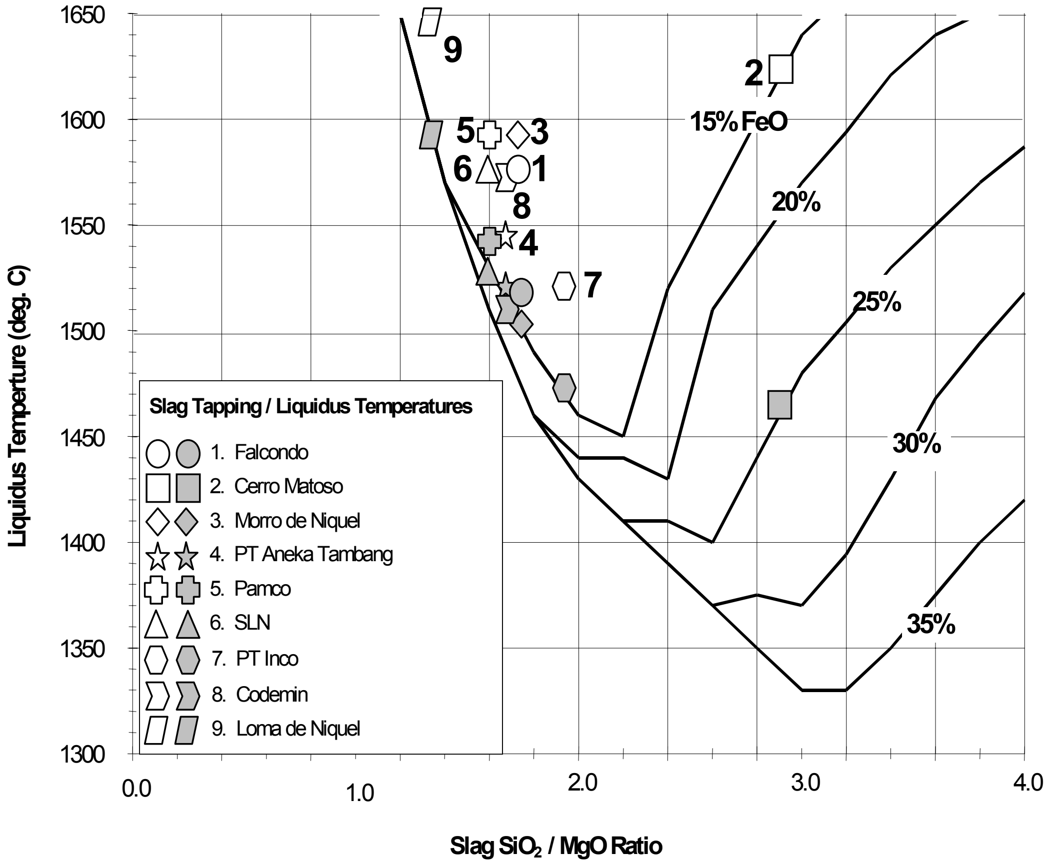

Figure 3. Slag tapping and liquidus temperature pairs for various ferro-nickel operations, depicted as a plot of slag liquidus vs. SiO_2/MgO ratio for various FeO contents [2].

For furnaces where the metal liquidus is low (Pamco, SLN, PT-INCO), the slag does not need to be highly superheated because the required temperature for tapping metal is readily available.

For furnaces making low-carbon ferro-nickel with high metal liquidus (Falcondo, CMSA), the slag temperature must be set to provide the required metal temperature for tapping. The slag superheat is then determined by the slag's liquidus. Falcondo and Loma de Niquel slag have high liquidus temperatures, and therefore relatively low slag superheat. CMSA slag has a lower liquidus temperature and hence higher slag superheat.

3. FURNACE THERMAL CONSIDERATIONS

The thermal capacity and hence type of sidewall cooling required for furnace integrity (bath containment and long campaign life) is determined mainly by the magnitude of the slag superheat, as explained below and shown in Figure 4.

With low superheat levels around 50°C, falling water film cooling is sufficient, as applied at Loma de Niquel for example. With slag superheats of 150-200°C, characteristic of those furnaces operating with less favourable SiO_2/MgO ratio such as CMSA and others, more robust wall cooling is required. The CMSA furnaces, the highest power ferro-nickel furnaces existing in the world, have a high slag superheat and a requirement for more robust cooling methods due to the metal and slag characteristics illustrated in Figure 2 and Figure 3.

As detailed in the section on high voltage shielded-arc practice below, total furnace power need not be a direct determinant of slag superheat, sidewall heat flux or sidewall cooling requirement.

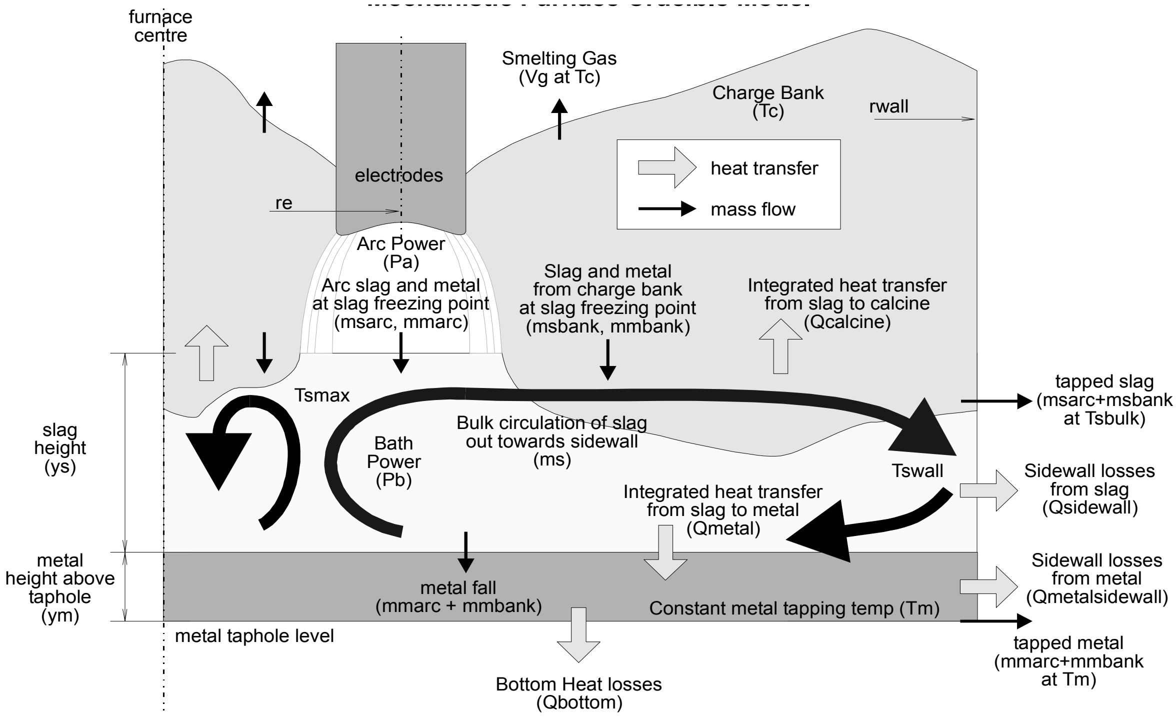

Figure 4. Furnace thermal model [3].

Referring to Figure 4, the portion of the furnace power input liberated by resistance heating of the slag bath is the decisive factor for furnace sizing and thermal design. Most of the energy generated in the slag bath is transferred to melting the calcine by convective heat transfer according to the following equation (neglecting sidewall and bottom heat losses to simplify the synopsis of the Hatch model presented here):

$$P_b = h_C \; A_b \; (T_{S\;bulk} - T_{S\;MP}) \tag{1}$$

where: P_b = bath power

h_C = heat transfer coefficient between slag bath and calcine

A_b = bath cross-sectional area,

$T_{S\,bulk}$ = slag bulk temperature (tap temperature)

$T_{S\,MP}$ = slag melting point (liquidus temperature)

Rewriting equation (1):

$$\Delta T_{SH} = \frac{1}{h_C}\left(\frac{P_b}{A_b}\right) \tag{2}$$

where: ΔT_{SH} is the slag superheat, and $\left(\frac{P_b}{A_b}\right)$ is the bath power density.

Equation (2) shows that with covered-bath conditions, the slag superheat is proportional to the bath power density.

The second important consideration for furnace thermal design is the heat transfer to the sidewalls. The main objective here is to freeze a layer of frozen slag on the brick hot face. This frozen slag protects the wall from erosion/corrosion by liquid slag, and the wall is then said to be in thermal equilibrium. The heat transfer to the wall is given by:

$$\left.\frac{Q}{A}\right|_{WALL} = h_W \left(T_{S\ \ bulk} - T_{S\ \ MP}\right) = h_W\ \Delta T_{SH} \quad (3)$$

where: h_W = heat transfer coefficient between slag bath and furnace wall.

Inserting equation (2) into (3) results in:

$$\left.\frac{Q}{A}\right|_{WALL} = \left(\frac{h_W}{h_C}\right)\left(\frac{P_b}{A_b}\right) \quad (4)$$

Equations (3) and (4) show that the equilibrium heat flux through the wall is also directly proportional to the bath power density and the slag superheat, as well as to the heat transfer coefficient, h_w, between the slag and the wall. This heat transfer coefficient depends on slag velocity or stirring, which in turn is dependent on thermal buoyancy forces and electromagnetic forces.

At low slag superheat, falling water film shell cooling or copper fingers are sufficient. At higher slag superheat levels, as experienced at CMSA and expected for high power furnace operations, more capable and robust coolers, such as Hatch waffle coolers, are required.

Other methods of decreasing the slag to metal temperature difference are decreased slag layer thickness and decreased hearth thermal conductivity.

Decreased slag-metal taphole distance is aimed at decreasing the nominal slag layer thickness that decreases the bulk slag-metal temperature difference by decreasing the distance between the hot slag under the electrodes and the top of the metal bath. The practical minimum slag depth is in the order of 0.5 to 0.75 m (normal slag depths are in the order of 1.0 m). Shallower slag depths provide less flexibility and demand near continuous slag tapping, and can lead to operating problems including increased metal losses and electrical instability. Increases in metal temperature in the order of 20-30ºC can be expected for a slag depth reduction from 1.0 to 0.75 m. A less conductive hearth design will reduce metal heat loss and hence increase metal tapping temperature. However, a more insulating hearth will result in a thinner protective frozen metal build-up (heel) on the hearth.

4. WALL COOLING

High slag superheat levels, whether caused by ore characteristics, high current operation, or the need for an adequate metal tapping temperature, require robust cooling measures for the furnace sidewalls. In these situations, falling water film cooling and even finger coolers are marginal, especially for inadvertent process upset conditions.

Copper finger cooler technology, essentially cooling elements penetrating into the furnace brickwork, but with all cooling water passages external to the furnace shell, were patented by Hatch in the early 1970's [4]. This technology was first implemented on Falcondo's ferro-nickel furnaces, closely followed by the furnaces at PT-Inco [5]. Plate type cooling is an extension of the finger-cooling concept, designed to withstand higher sidewall heat fluxes while still maintaining the water passages outside the furnace shell for maximum safety. The need for robust cooling systems has accelerated in recent years, in response to the containment requirements of intense smelting processes. Examples that present particularly difficult containment issues include the copper converting furnaces at Kennecott Utah Copper (Kennecott-Outokumpu converting process) and Falconbridge Kidd Creek (Mitsubishi converting process). For these applications, Hatch developed and installed waffle-type cooling elements, so named because they have dove-tailed grooves on the hot face which are able to retain rammed or cast refractory, or frozen slag build-up. [6] The copper elements actually form the furnace wall, so that there is no requirement for residual refractory brick to provide furnace structural integrity. These waffle-type cooling elements provide furnace integrity even where residual equilibrium accretion or refractory is less than a few centimeters thick.

This waffle technology has recently been successfully transferred to the ferro alloy industry. Among the most demanding applications is Chambishi's ferro-cobalt DC furnace, in which Hatch waffle coolers were installed around the furnace hearth perimeter down to the skew level [7]. As the coolers extend below the slag-metal interface they are exposed to heat fluxes that are an order-of-magnitude greater than in the slag zone. This requires much higher thermal capacity cooling elements than those intended only to freeze slag.

Waffle type of cooling is also installed at the slag / metal interface of Cerro Matoso's new furnace, in response to the high heat flux at the slag / metal interface that occurs if the metal temperature exceeds the slag liquidus. Due to the vertical movement of this interface with changes in metal level caused by production and tapping, an area of the furnace wall is alternately in contact with either metal or slag. High metal temperature and/or low slag liquidus can cause melting of the protective slag accretion in this area, necessitating robust cooling, e.g., waffles, at the slag metal interface.

Air-cooled fins are a new technology for cooling areas of furnaces with less intense heat fluxes. Copper fins are attached to the furnace shell and enclosed in a duct with forced airflow. The fins enhance the heat removal rate by a factor of approximately five times over forced air cooling alone, hence the fin system has found application as a substitute for traditional falling water film cooling. The advantage of air-cooling is avoidance of water, which can cause brick hydration, due to water ingress through holes in the furnace shell, and steam explosions if the water comes into contact with hot metal.

5. HIGH VOLTAGE SHIELDED-ARC PRACTICE

Most of the world's major ferro-nickel producers now practice the shielded-arc method of smelting listed in Table 1, first developed by Falconbridge Dominicana and Hatch in the 1970's [8].

Table 1. Ferro-nickel furnace shielded-arc operations.

Operation	**Year Shielded-Arc Adopted**	**Number and Size of Furnaces presently operated**	**Hearth power density (total power/hearth area) (kW/m^2)**
Falcondo (Dominican Republic)	1971 (pioneered)	2 x 60 MW	360
Cerro Matoso (Colombia)	1985	2 x 75 MW	230
PT Inco (Indonesia)	1986 (began upgrades)	4 x 70 MW	300
Societé le Nickel (New Caledonia)	1990's	3 x 50 MW	140
Loma de Niquel (Venezuela)	2002	2 x 45 MW	200

The shielded-arc method enables the majority of the power to be transferred directly from the arc to the calcine. In contrast, immersed electrode operation relies on resistance heating of the slag bath, and melting of the overlaying calcine by contact with circulating superheated slag. The two practices are compared in Figure 5 and Figure 6 [9].

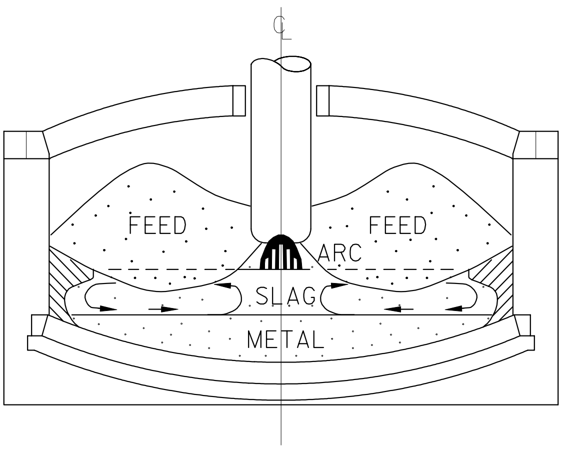

Figure 5. Shielded-Arc.

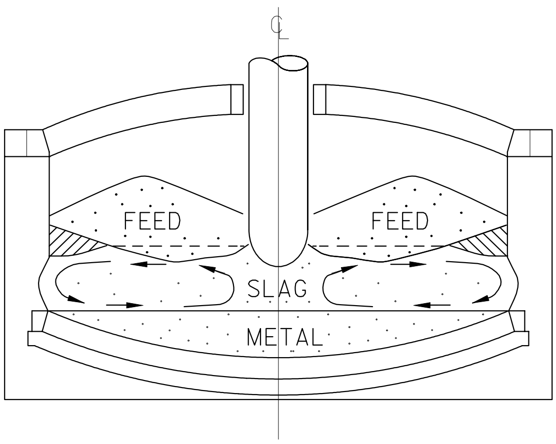

Figure 6. Immersed Electrode.

The immersed electrode method is much less effective, as the required slag superheat, especially at high production rates, results in high sidewall heat flux and refractory wear of the walls as indicated in Figure 6. The main benefits of shielded-arc practice are high-productivity furnace operation (i.e. high throughput rate per unit hearth area), with only modest dependence on wall cooling requirements and without the high heat losses resulting from high current, high slag superheat operation. Furthermore, the temperatures and heat losses from the freeboard are modest relative to the alternative open-arc practice by virtue of the calcine cover surrounding the arcs (Figure 5).

Traditional immersed electrode or short (brush) arc operation have several disadvantages:

- Higher sidewall heat losses and electrical heat losses
- High current operation results in high electrode consumption
- Design for high current operation increases transformer, buswork and electrode physical size and cost.

As described in the original patent on this method of operation [10], the proportion of the total furnace power in the arc (P_a) is arranged to be substantially greater than that in the slag bath (P_b), (i.e., P_a / P_b ≈ 5), to provide heat for melting the calcine preferentially fed to and surrounding the arc. Arcs are formed between the electrode tips and the slag surface, and the electrode tips are surrounded with charge so that the arc exists in a cavity.

The power released in the arc and the bath are directly proportional to their respective resistances. For the simplified case of one phase and a power factor of 1,

$$\frac{P_a}{P_b} = \frac{R_a}{R_b} \tag{4}$$

where: P_a = arc power
P_b = bath power (as previously defined in equation 1)
R_a = arc resistance
R_b = bath (slag) resistance
Also, Ohm's law states:

$$P_t = \frac{V_t^2}{R_t} \tag{5}$$

where: P_t = total power
Vt = total voltage
R_t = total resistance

Also,

$$R_t = R_a + R_b \tag{6}$$

Combining equations 3, 4 and 5:

$$\frac{P_a}{P_b} = \frac{V_t^2}{P_t R_b} - 1 \tag{7}$$

From equation 7, one can see that to achieve the shielded-arc benefits from a high P_a/P_b ratio, the voltage must be maximized. Bath power need be sufficient and only to provide metal and slag temperatures adequate for tapping. Minimizing the slag layer thickness minimizes the bath power required to maintain slag and metal temperatures.

As shown in Figure 5, high voltage shielded-arc operation at moderate power promotes a protective frozen slag accretion on the walls, in contrast to the wall erosion of the high current immersed electrode case for the same power depicted in Figure 6. This accretion can be quantified by tapping a known mass and volume of slag, and measuring the level reduction resulting from the tap, in order to calculate an active bath area (ABA) as set out in US Patent 4,273,576 [11]. If the ABA is less than the furnace as constructed internal dimensions, the existence of a protective frozen slag layer on the refractory hot face can be inferred.

By adjusting the P_a/P_b ratio, the thickness of this frozen layer or crust on the walls can be controlled. Without forced cooling of the walls the ABA must be strictly limited to approximately 30-60% of the furnace hearth area, depending on the SiO_2/MgO ratio. With reasonable voltages and furnace size this relatively small ABA constrains furnace power and throughput; hence forced cooling, such as provided by water-cooled copper elements, has been widely adopted in conjunction with high voltage. This technology enables ABA of 100% or slightly more of the original crucible size, with resulting increase in furnace power and throughput to the present 75 MW and beyond.

High voltage however results in decreased furnace stability and increased power swings. This can be mitigated through the application of new control and power electronics technology, as discussed in the following section.

6. FURNACE CONTROLS

Ferro-nickel furnace operating power has reached 75 MW with moderate electrode current ranging from 11 to 35 kA, but electrode voltages well over 1000 Volts and arc lengths up to 50 cm. To properly regulate power delivery with the long arcs resulting from high voltage operation, improvements have been made to the hoisting hydraulics, process controls and furnace electrical power supply.

High-speed hydraulics, with electrode speeds exceeding 2000 mm/min, are in use on production ferro-nickel furnaces. Due to their large mass (inertia) and in order not to break the relatively fragile Soderberg electrodes commonly used on ferro-nickel furnaces, there are practical limits to electrode acceleration.

Improvements have also been made to the feed delivery system to accurately meter feed into the furnace.

With increased furnace power there is a requirement for more sophisticated and integrated controls to ensure steady state operation. An integrated furnace system should contain the following control modules [12]:

- Power control - the power controller provides operating points tailored to the measured slag bath resistance.
- Feed control - feeding based on actual amount of material charged (using bins on load cells) and actual power delivered to the furnace.
- On-line heat balance – continuously monitor surface temperatures, water flow and temperature rise, etc., to calculate energy losses and adjust power and feed balance accordingly.
- Slipping control - recommend slip for each electrode based on actual conditions (power, current, limit switches).
- Supervisory control - coordinate action of other controllers.

In addition to integrating the actions of the various software modules, the sophistication of the individual control modules has been increased. For example, an advanced control module called “Primary Voltage Compensation” has been added to the Hatch furnace power controller. At sites where the power grid is variable and the primary voltage on the furnace transformer(s) fluctuates, potential transformers (PTs) are added to measure the changes in primary voltage. The Hatch Furnace Power Controller (FPC) responds to the measured changes in primary voltage by altering the transformer tap selection and electrode position to maintain both the power and current setpoint.

Another advanced control module is used in plants were there are several furnaces on the same high-voltage bus. This module balances the total power draw of a group of furnaces. For example, if an electrode on one of the furnaces strikes a limit switch and as a result unbalances the furnace power draw, the individual electrode setpoints on the other furnaces on the grid are temporarily altered to balance the total draw of all the furnaces.

As previously discussed, in a smelting furnace the ratio of arc to slag bath power is one of the key parameters. If the power delivered to the slag bath is too high, the slag bath temperature and stirring will increase resulting in increased refractory wear. If it is too low the metal and possibly also the slag will be too cold and difficult to tap. Hatch has developed a system to provide an on-line estimate of slag bath resistance; this system has been installed on several smelting furnaces. Figure 7 shows slag bath resistance over time for a ferro-nickel furnace, with the resistance fluctuating substantially over the course of a typical day.

To accurately control arc power versus bath power, it is thus clear that the slag resistance estimate must be one of the key inputs into furnace power control module. The bath power based control module allows the control of both the total power delivered to the furnace as well as the ratio of arc to bath power.

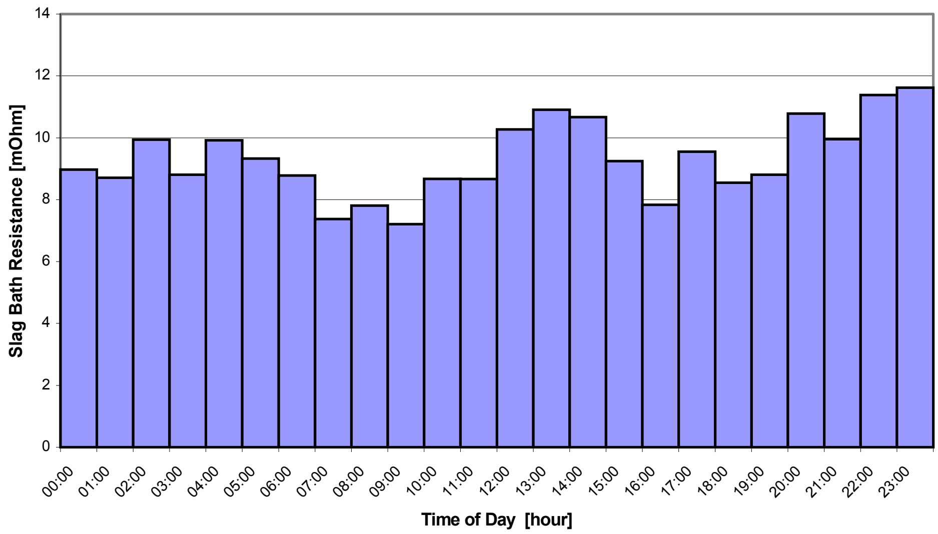

Figure 7. Measured slag bath resistance.

Conventional electrode control systems regulate power by positioning electrodes and selecting the transformer tap position. Due to the mass and inertia of the electrodes, this is typically a slow process wherein power fluctuations of less than a few seconds are <u>not</u> fully corrected. To provide enhanced power control, Hatch has developed and implemented on a 60 MW furnace, a power electronic device called a Smart Predictive Line Controller (SPLC) for AC furnaces [13]. The patented SPLC technology is a controlled current limiting reactor installed between the furnace and the power supply and is used to stabilize the power delivered to an AC furnace, as demonstrated in Figure 8. The controlled reactor is a large size (approximately 30 Ohm), and can effectively eliminate power peaks.

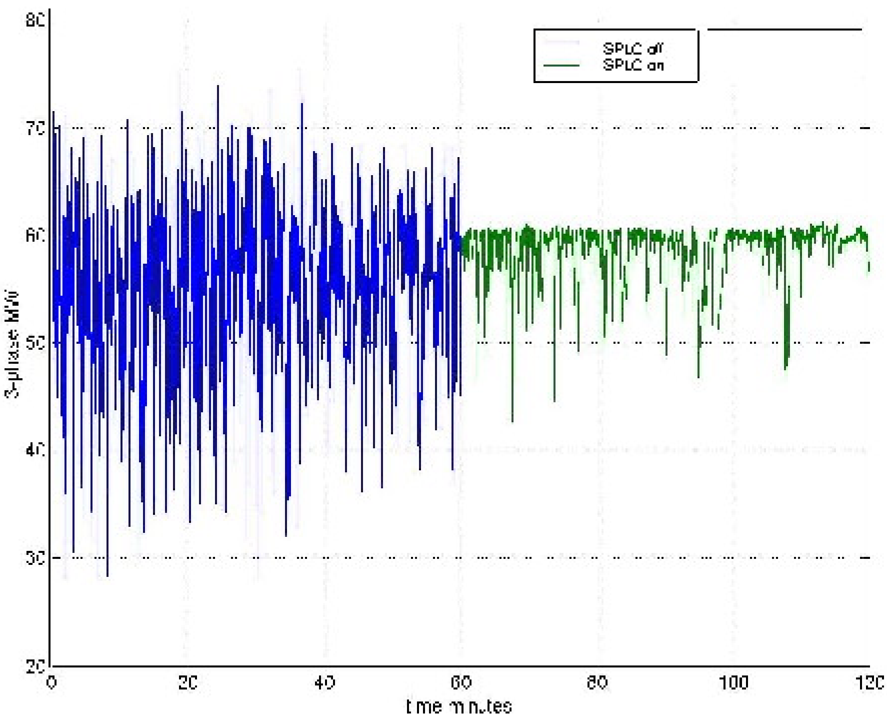

Figure 8. SPLC Performance (MW vs. time) at 60 MW setpoint.

A 50 kW test furnace was constructed to verify the combined operation of electrode positioning and SPLC. The measured result was a 3 to 1 reduction in power fluctuations when the SPLC was enabled. A 60 MW production version of the SPLC was commissioned in mid 2003 at Falconbridge Dominicana. Power swings (standard deviation from setpoint) at this production scale have been similarly reduced. The graph in Figure 8 provides some measured data from the SPLC during start-up. One of the key features of the SPLC is the simplified operation. While the SPLC provides significantly more flexibility in the operation of the furnace than the traditional power regulation system, the operators can control the furnace in the same way with the SPLC on or off. Figure 9 gives an example of the operator screen for integrated SPLC and electrode control.

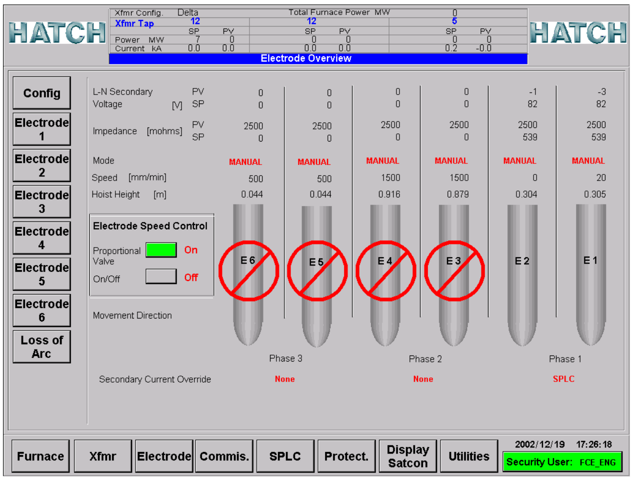

Figure 9. Operator screen with SPLC.

A furnace Expert system will provide the next generation of crucible monitoring and operator guidance. Hatch has set-up a consortium of furnace plants to work on expert systems. The first area of focus for the expert system is the furnace tap holes. Furnace tap blocks are high-wear items and the tap block expert system monitors the tap block instruments to provide an improved indication of when maintenance will be required.

7. DC FURNACES

Nickel laterite smelters using the conventional RKEF process (rotary kiln-electric furnace) require special measures to control the recirculation of fine material, normally by agglomeration. These fines could be smelted directly in immersed-electrode or open-bath AC furnaces, or in open-bath DC furnaces, as used in South Africa for smelting ferro-chrome fines. A DC furnace treating ferro-nickel dust generated at Cerro Matoso was successfully tested in 1994 [14].

The major advantage of an open-bath DC furnace is its ability to process 100% fines. However, the open-bath results in a hot freeboard typically requiring water cooling of the upper walls and roof; hence the heat losses are higher than for shielded-arc AC furnace. The bottom anode of a DC furnace can also cause problems with regard to destructive arc skewing. But by using a number of side anodes around the hearth periphery, connected to the bus with variable resistance, this problem can be mitigated [15]. Adjusting the resistance on individual side anodes has been shown to influence the arc alignment. After demonstrating this anode design at small scale on a ferro-nickel test furnace, it was successfully scaled up on Eramet Gulf Chemicals' 10 MW DC furnace treating ferro-vanadium, -cobalt, and -nickel containing fines.

Falconbridge is developing a process that utilizes an open-bath DC furnace treating 100% fine laterite ore [16]. This flowsheet is intended to avoid the dust problems plaguing RKEF plants by grinding the ore to –1 mm and using totally enclosed pneumatic reactors for drying, calcining, and reducing the ore prior to smelting. Flash drying and flash calcining can be used (as is commonly done in the cement industry), rather than rotary dryers. Fluid bed reactors can then be used in place of the traditional rotary kiln for pre-reduction before feeding to a DC furnace.

8. CONCLUSIONS

Several furnace technologies have been discussed in this paper, some like high voltage and water-cooled copper elements, having already gained relatively wide use, and others like SPLC power smoothing electronics, only recently proven.

These technologies, especially when applied in an integrated fashion, have enhanced ferro-nickel production by enabling:

- treatment of high-grade ores with unfavourable SiO_2/MgO ratio.
- large, high intensity furnaces providing low operating and capital cost per unit of production, through economies of scale.

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