INTEGRATED FURNACE CONTROLS: IMPLEMENTATION ON A COVERED-ARC (SHIELDED ARC) FURNACE AT CERRO MATOSO

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ABSTRACT

The paper describes the components of an Integrated Furnace Control system for covered-arc (shielded arc) smelting with results from the recently started 75 MW Cerro Matoso Line 2 Furnace. The paper starts with a review of the mechanisms of power and feed input and heat losses in the shielded-arc smelting process, and describes how the details of the control system are tailored to the process. The control modules of a covered-arc smelting furnace are described including measured results and screen captures. This paper focuses on Integrated Furnace Controls tailored to shielded-arc smelting, but similar approaches have been recently applied to other furnace processes including immersed-arc smelting.

1. INTRODUCTION

The efficient operation of a shielded-arc smelting furnace requires good control of the power and feed delivered to the furnace to maintain the arc cover and the slag bath temperature. This paper describes the design of a complete Integrated Furnace Controller for shielded-arc smelting with sample results from the recently installed Cerro Matoso Line 2 Furnace. The Hatch Integrated Furnace Controller includes the following software modules and associated instruments: Furnace Power Controller; Furnace Feed Controller; On-line Heat Balance, and Supervisory Controller. The function of each of the modules is described below, including some of the critical design considerations. The focus of the integrated controls is to provide a high level of smelter automation through the comprehensive and coordinated control of the smelting furnace.

Results from the Line 2 Furnace in Colombia are used to illustrate the covered-arc smelting Integrated Furnace Controls. The smelter processes laterite nickel ore mined by open-pit methods. The smelter produces high-purity, low-carbon ferronickel granules, which are used exclusively in stainless steel production. Production was expanded with Line 2, which commenced production in January 2001. The expanded operation makes Cerro Matoso one of the largest ferro-nickel producers in the world.

2. THE COVERED-ARC (SHIELDED-ARC) SMELTING PROCESS

The covered-arc smelting process (also called the shielded-arc smelting process) was developed in the late 1960s and early 1970s as a technique to increase the power intensity in the furnace crucible without the problem of refractory erosion encountered with immersed electrode smelting [1, 2, 3]. The mechanisms of power input, heat transfer and mass flow in the furnace crucible with the shielded-arc smelting process are shown in Figure 1. The smelting process details are closely coupled to the control system design including the required software modules.

The electrical power input to the furnace has two components: 1) arc power, and 2) bath power. In Figure 1, the arc power is labelled (P_a) and is the power delivered to the furnace by the long powerful arc between the electrode tip and the surface of the slag bath. The slag bath has an average height (ys) and is represented by the white area in the middle of Figure 1. The charge material covers the electrode tip and the arc power heats

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the charge instead of the furnace roof. The bath power is labelled (P_b) and is the power delivered to the slag bath by the resistance or Joule heating caused by the electrode current flowing through the slag layer.

The Furnace Power Controller is the part of the Integrated Control system that regulates the power delivery to the furnace. The Furnace Power Controller not only controls the total power delivered to the furnace but also the power balance between electrodes and the ratio of arc to bath power (P_a/P_b). The ratio of arc to bath power is a critical control parameter: Too little slag bath power will make the slag colder and more viscous, hence difficult to cleanly separate the matte or metal, and also difficult to tap. Too much slag bath power will increase heat transfer from the furnace walls due to increased slag temperature (i.e., increased superheat above its liquidus) and more vigorous stirring. This increased heat flux results in increased refractory wear and excessive furnace heat losses.

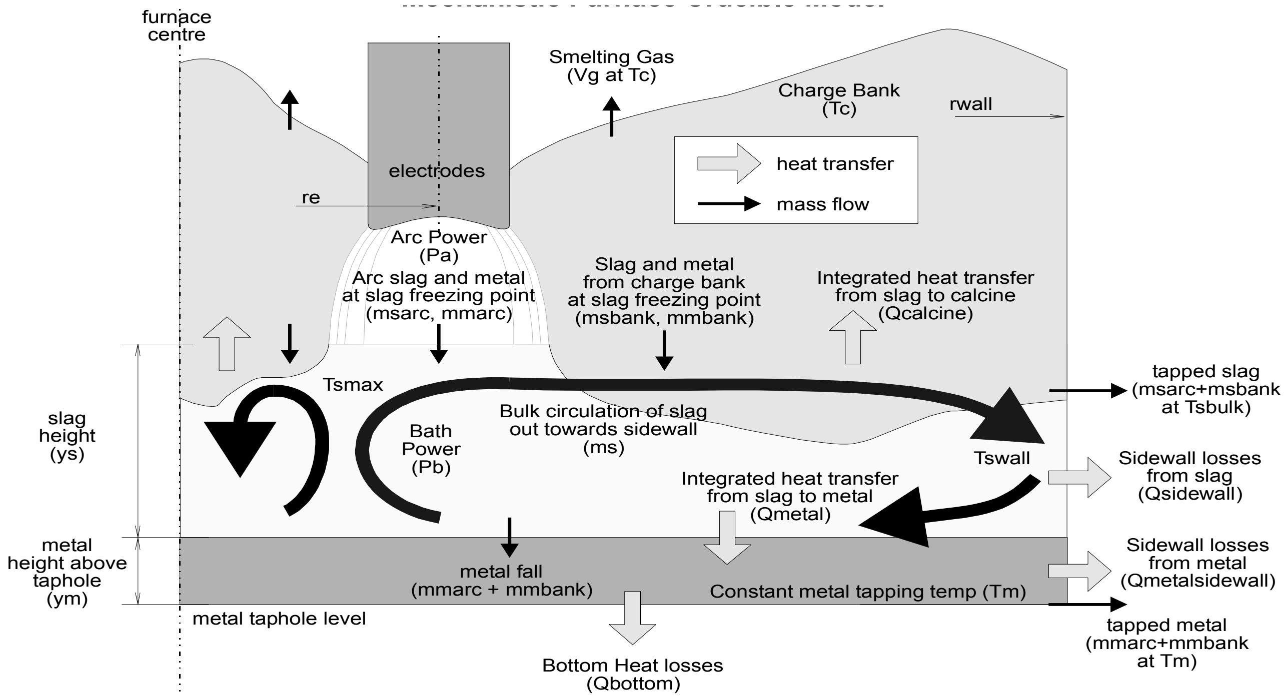

Figure 1. Shielded-Arc Smelting Process [3].

The furnace feed material, or calcine, is supplied from a rotary kiln and stored above the furnace in feed bins. The hot calcine in the feed bins is metered into the furnace through feed ports in the roof of the furnace from the top of Figure 1. The charge banks are shown as the grey layer above the slag bath and surrounding the electrode tip. The feed ports are distributed over the roof of the furnace so that feed can be directed to specific furnace areas.

The Feed Controller is the part of the Integrated Furnace Control system that is responsible for maintaining the level of the charge banks. Too little feed, especially around the electrodes, will result in an uncovered (non shielded) arc and a significant increase in roof temperature due to direct exposure to the arc. Too much feed will fill the furnace to the roof, and potentially interfere with the off-gas system and cause accretions or false roofs to form.

The heat leaving the furnace crucible is shown in Figure 1 as Bottom Heat losses (Qbottom) and Sidewall losses from the metal and slag layers (Qmetalsidewall, Qsidewall). In addition to the sidewall heat losses, heat is lost by the tapped slag (msarc+msbank at Tsbulk) and the tapped metal (mmarc+mmbank at Tm). The slag and metal accumulation in the furnace are represented by the metal height (ym) and slag height (ys) in Figure 1.

The On-line Heat Balance module in the Integrated Furnace Control system is responsible for tracking heat losses and metal accumulation in the furnace. Tracking of the heat losses allows the power to feed ratio to be finely balanced providing maximum efficiency and tracking of metal levels. Monitoring of the metal levels in the furnace allows scheduling of the metal and slag taps, and avoidance of excessive metal or slag levels detrimental to the furnace.

3. THE CERRO MATOSO SA LINE 2 FURNACE

Cerro Matoso operates two Ferro-nickel furnaces in Colombia, South America that employ the covered-arc smelting process. The Line 1 Furnace has been in operation since 1980. The Line 2 Furnace was designed by Hatch with the most advanced cooling and binding technologies, as well as the control system described here, to enable high power operation. This new furnace was commissioned in 2000.

The Line 2 Furnace incorporates a significant number of instruments to provide a high level of information about the process.

Some of the instruments on the furnace are:

- Power consumption meters on the furnace
- Electrode slip meters
- Load cells on the feed bins
- Water temperature thermocouples at the entrance and exit of each water cooled element
- Water flow meters at the entrance and exit of each water flow circuit
- Two level refractory thermocouples
- Redundant thermocouples
- Furnace pressure monitor
- Furnace temperature thermocouples
- Air flow meters
- Air Thermocouples

4. THE CONTROL SYSTEM MODULES

To achieve the objective of maximum production and efficiency it is necessary to have coordinated control software architecture.

The integrated furnace control system for the Line 2 Furnace includes four main modules or controllers:

- Power Controller
- Feed Controller
- An On-line Heat Balance module;
- Supervisory controller

These four main modules are described in greater detail below, including some measured results from the Line 2 Furnace. In additional to the four main modules, control systems were also provided for the off-gas system, the rotary kiln and the electrode slipping device. The CMSA Line 2 control system was constructed using a combination of an ABB DCS and networked Allen Bradley Programmable Logic Controllers.

4.1 The Furnace Power Controller

The Furnace Power Controller controls the total power delivered to the furnace to:

- Control slag bath power to maintain target metal and slag temperatures and acceptable side-wall heat flux
- Provide stable long arc operation to enable high furnace power production, without excessive sidewall heat flux
- Reduce the occurrence and duration of loss of arc.

Referring to Figure 1 detailing the covered arc smelting process, the Furnace Power Controller is used to control the power delivered to the furnace including balancing the power delivered by the three electrodes and controlling the ratio of arc to bath power (P_a/P_b).

The bath power is controlled to a value just sufficient to provide metal and slag temperatures adequate for clean metal/ slag separation and for tapping. Any bath power beyond this amount is undesirable, as it would result in higher than necessary sidewall heat flux, heat loss and refractory erosion. To achieve these objectives of controlling power delivery, the furnace power controller positions the electrodes vertically and operates the transformer tapchanger.

4.1.1 Tap Calculation

The transformer tapchanger alters the voltage applied to the electrodes in a stepwise fashion. The tapchanger on the Line 2 Furnace has 34 tap positions. The transformer tapchanger allows the power setpoint entered by the operator to be achieved over a range of electrode currents. Specifically, the higher the tap number, the higher the electrode voltage and the lower the electrode current for the same power setpoint.
In the covered-arc smelting process the selected transformer tap position controls the ratio of arc to bath power. Specifically, the higher the tap position the lower the electrode current and the lower the slag bath power. The relationship between the electrode current and the slag bath power is given by:

$$P_b = R_{bath}\left(I_a^2 + I_b^2 + I_c^2\right) \qquad (1)$$

Where P_b is the slag bath power, which depends on the slag bath resistance R_{bath}, and the individual electrode currents are I_a, I_b, I_c.

R_{bath} is measured by a "dip test", whereby the electrodes are immersed into the slag a known distance, and the corresponding voltage and current recorded; from this information at variouos immersions (and accounting for electrode diameter), R_{bath} can be claculated. This methodology and calculation can be automated. The Furnace Power Controller uses Equation 1 to calculate the electrode current setpoint using a target bath power that results in desired metal and slag temperatures with acceptable sidewall heat flux. An on-line Power, Voltage, Current (PVI) calculation determines the target tap position from the power and current setpoints. An on-line estimate of slag resistance and the resulting target electrode current and transformer tap position is displayed to the operator.

There are two control modes for the transformer tapchanger. In manual mode the operator selects the tap position. When the transformer tapchanger is placed in computer control, the tap position is adjusted by the control system to achieve a target slag bath power.

4.1.2 Electrode Positioning

The power on the individual electrodes is balanced by positioning the electrodes. The Furnace Power Controller includes a separate control loop for each electrode with the main inputs to the control loop being the electrode voltage and electrode current. The measured electrode voltage and current are used to position the electrodes to achieve an impedance setpoint.

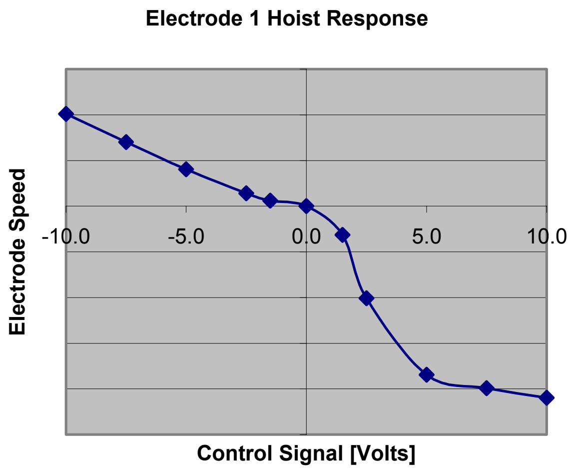

Figure 2. Response of Electrode Hoist to a Control Input.

The 1.8 m diameter, Søderberg electrodes used on the Cerro-Matoso furnaces are positioned using hydraulic cylinders and servo valves to provide variable speed with fast lowering speed. Electrode hoists are both non-linear in their response to the control input and include time delay – both the non-linear response and the time delay constrain the performance of the electrode regulation system. To provide good performance, the electrode regulation system is tuned taking into account the hoist response as measured during commissioning. Figure 2 above shows the measured hoist response to a control input.

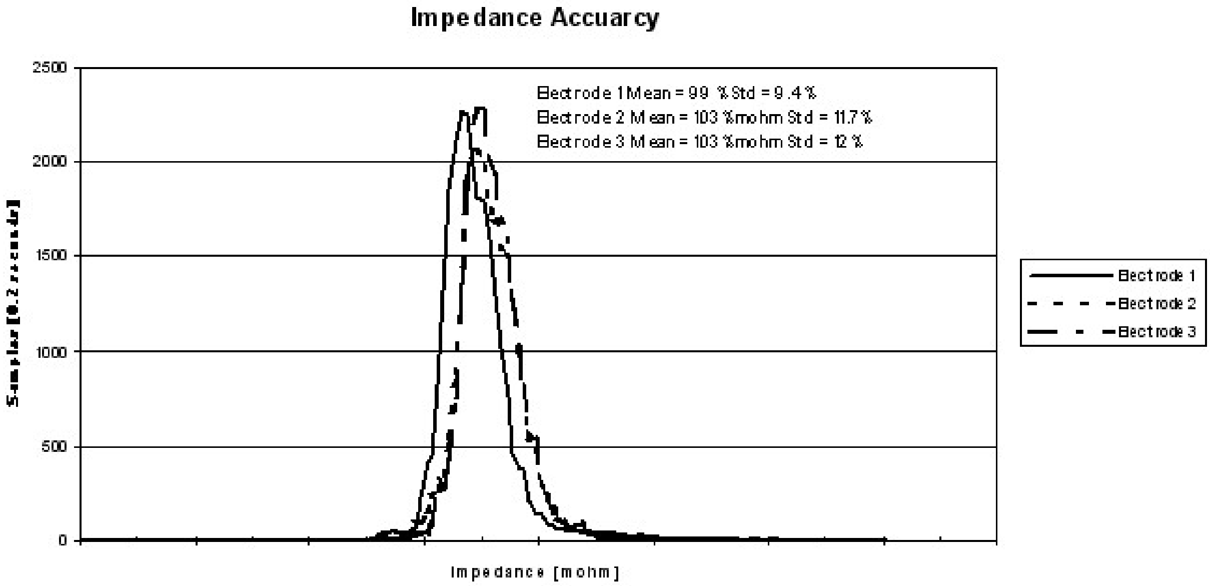

Figure 3. Measured Impedance Histogram for the Line 2 Furnace.

Figure 3 shows the measured impedance histogram for each of the three electrodes. The impedance histogram was produced by sampling the measured electrode impedance once every 0.2 seconds and placing the measured results in impedance bins. The graph shows the measured results for an impedance setpoint of 100%. The average electrode impedance is within 3% of the setpoint with a low standard deviation of about 10%. This is very close adherence to the setpoint for a process where a large proportion of the total furnace power is liberated in the arc. Figure 3 also shows that the combination of electrode hoist and electrode regulation system achieve a close match to electrode impedance setpoint and essentially the same impedance on each of the three electrodes resulting in balanced power delivery to the furnace.

4.2 Feed System Controller

Referring back to Figure 1 detailing the covered-arc smelting process, the feed control system distributes the charge to maintain a covered-arc operation, which is vital to a stable, reliable and efficient operation.

The Furnace Feed Control Module includes a number of innovative features:

- The charge is distributed either by
- Assigning an *operator-specified* percentage of the total feed to the Center (between electrodes), Middle (around the electrodes), and Peripheral Zones (near the walls), or by
- Assigning a *computer-specified* portion of the total feed to individual feed pipes, based on power distribution in the furnace to concentrate more feed in the center of the furnace at higher furnace powers.
- The gate operation is *periodic,* i.e., fixed size charge slugs are fed through each feed pipe.
- Charge weight is measured by a loss-in-weight system and controlled by both weight and time information using a learning control mechanism in order to control actual batch size (further described below).
- Integrating the energy input per electrode in the computer-specified control mode controls charge timing.
- Estimates of the calcine level are used to adjust the feed distribution in order to maintain a covered arc operation.
- Bin feed rate is computed to sequence the bin filling operation.
- Bin refill schedule list is sent to the calcine transfer control system indicating which bin should be feed next.

To properly control the distribution of feed in the furnace, it is necessary to control the batch discharge size for each feed pipe. The batch discharge size is the weight of feed delivered to the furnace for each opening of the feed gate. There are a number of factors affecting the batch discharge size that vary over time including calcine temperature, number of pin gates in the feed pipe and amount of material in the bin. The furnace Feed Controller includes a learning algorithm that adjusts the gate opening time to deliver the desired batch discharge size even though several of the factors vary over time. For each batch through each feed pipe, the learning controller monitors the length of time the gate is open, the discharge amount and the reaction of the gate to the control signals (i.e., gate travel times), and so corrects its setpoints for the next operation of that particular feed pipe. The learning controller evaluates all of the observations of the last action on the feed gates and only uses information that it deems correct. The result is lower variation of the batch size compared to control based on fixed values of the above parameters.

Figure 4 illustrates the success of the learning batch size controller in reaching the batch setpoint accurately and consistently, irrespective of deviations in calcine temperature and bin level. In Figure 4, the bin level and calcine temperature are changing over a period of time, and the Feed Controller is adjusting the feed gate opening time to maintain a relatively stable batch size.

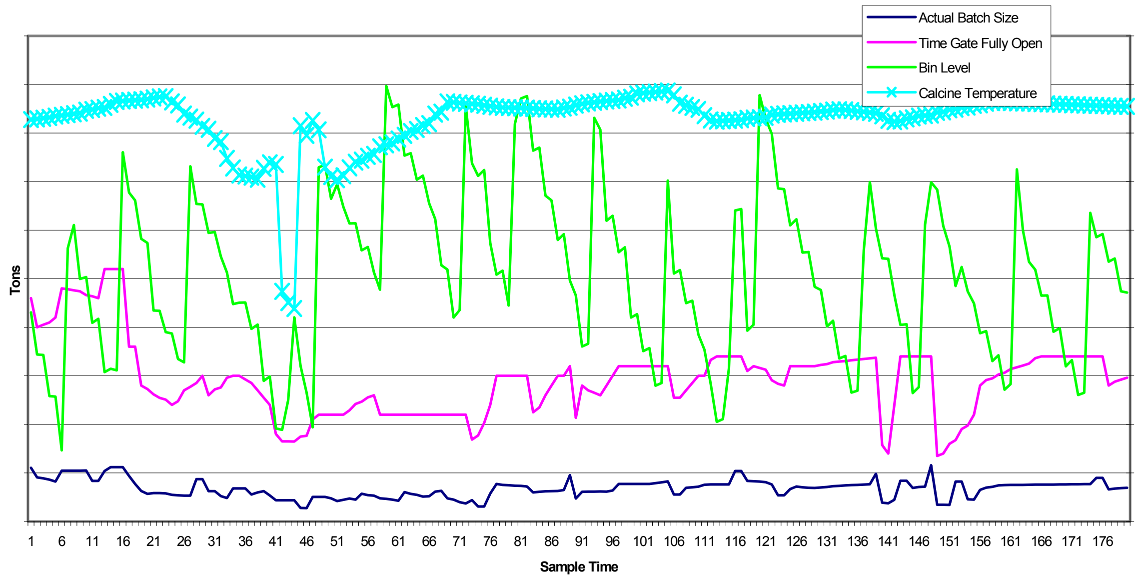

Figure 4. Relationship Between Batch Size, Gate Open Time, Bin Level and Calcine Temperature.

Table 1 presents statistics for feed batch size for two typical feed pipes on the Line 2 Furnace with a feed setpoint of 3 tonnes and a comparison to Line #1 performance for one observed data point.

The table shows that the batch discharge size closely matches the batch setpoint of 3 tonnes, especially when compared to the historically observed performance on Line #1.

Table 1. Statistics for batch discharge size for the Line 2 Furnace.

Feed Pipe Number	**Batch size statistics**				**Number of gate openings**
	Setpoint	**Average**	**Standard Deviation**	**Maximum**	
1	100%	80%	16%	101%	12
4	100%	104%	35%	181%	77
Line#1	100%			5000%	1

To accurately gauge the success of the furnace feed system, it is necessary to show how the furnace feed system affects the performance of the furnace. Cerro Matoso has developed an Arc Quantity Indicator (AQI) that is an index of the stability of the high voltage arc based on detailed analysis of the arc voltage and current waveforms.

A reduction in standard deviation of the arc quantity indicator value represents more stable arcing and thereby indicates stable furnace conditions. The standard deviation of the arc quantity indicator with the furnace feed in automatic and manual are given in Table 2. The Arc Quantity indicator is very sensitive to the environment of the arc. The feed system controls the environment of the arc by consistent regular feeding of the arc providing a constant shielded arc chamber environment by feeding material around the chamber at a regular rate. The Arc Quantity indicator standard deviation is most sensitive to consistency of feed rate, as long as the average feed rate is balanced with power. If the feed rate is under balanced to power, an open bath condition would result causing substantial change in the value of the Arc Quantity Indicator.

As shown in Table 2, the standard deviation of the arc quantity indicator is generally lower with automatic feeding, indicating more stable operation.

Table 2. Comparison of Arc Quantity Indicator with the feed system in automatic and manual.

	Standard deviation in Arc Quantity Indicator [Arc quantity is dimensionless and ranges for -100% to 100%]	
	Automatic	**Manual**
Electrode 1	9.48	18.17
Electrode 2	22.52	17.69
Electrode 3	11.41	43.14

The furnace feed system consistently and accurately ensures that feed is provided to the correct area of the furnace. In addition to the AQI, roof thermocouples provide feedback with high temperatures indicating areas of open bath, and “yo-yo’s” – rods connected to position indicators – are lowered through small ports in the roof onto the calcine piles or banks to provide feedback on the actual height of the piles.

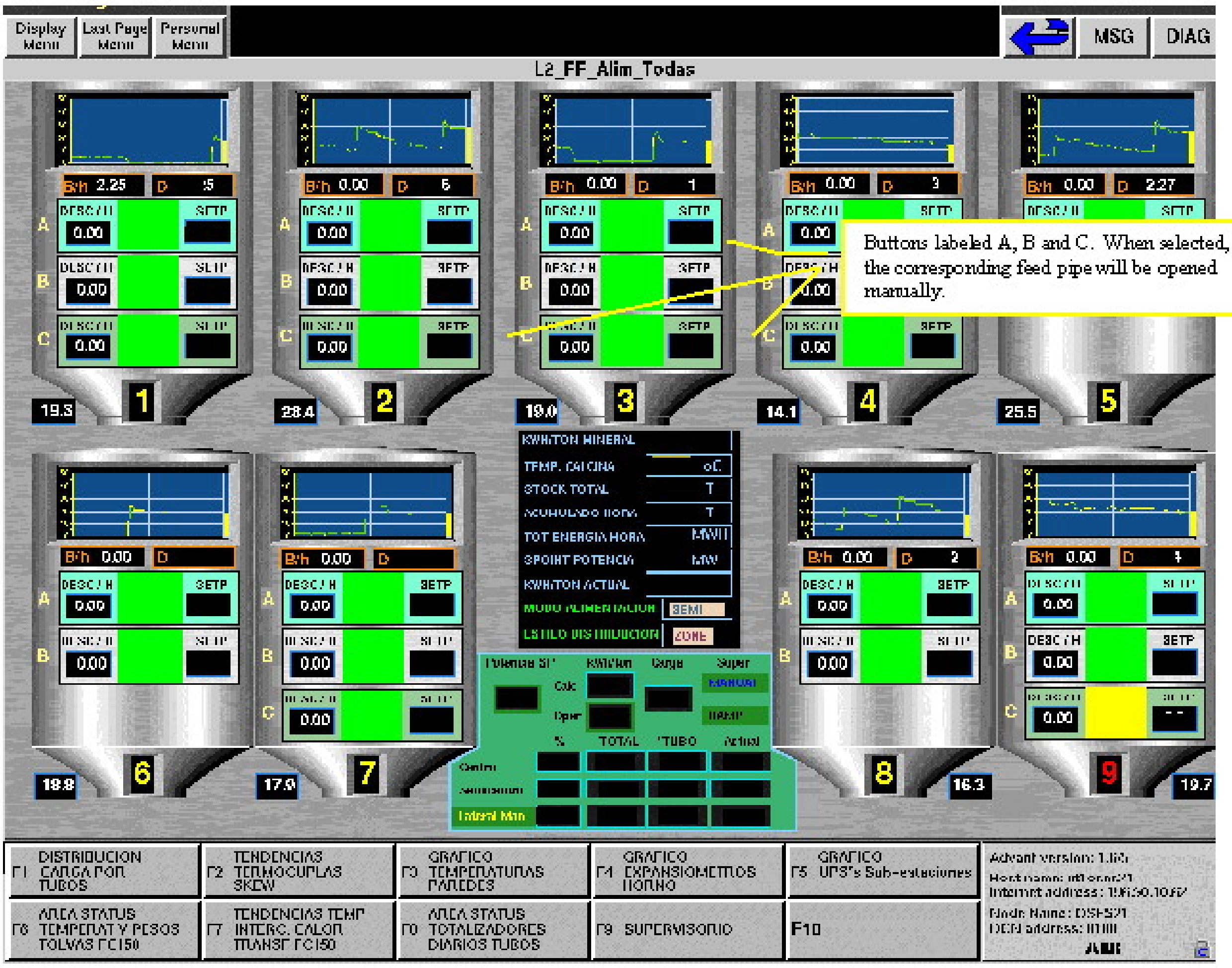

Figure 5. Feed Bin screen on Line 2 Furnace.

When there is insufficient material in a bin, the feed system accounts for the lack of material and delays the discharge of feed until the bin is refilled. Similarly if the batch discharged was larger than the set point, the feed system will increase the delay time between batch discharges to correct for the batch discharge size error. Figure 5 (above), shows the main furnace feed screen for the Line 2 Furnace that was modelled after the Line 1 screen.

The note on Figure 5 points to the buttons that are used by the operator to manually initiate feeding to locally modify the amount of calcine in the furnace. The operator can control the discharge of each pipe in semi-automatic mode with the furnace feed system controlling the batch size.

Figure 6 shows the Furnace Feed Controller detail screen. On the details screen, the operator has a list that is constantly updated to inform the operator which feed pipe will be selected next for feeding. Ideally there should only be one feed pipe number on the list, indicating that the feed pipe is being activated at the most opportune time. The screen in Figure 6 also provides a summary of the actual furnace feed distribution.

The operator also has a table listing the actual weight of feed charged to the different zones of the furnace. The furnace feed distribution summary table provides information that the operator uses to make fine adjustments to the feed distribution.

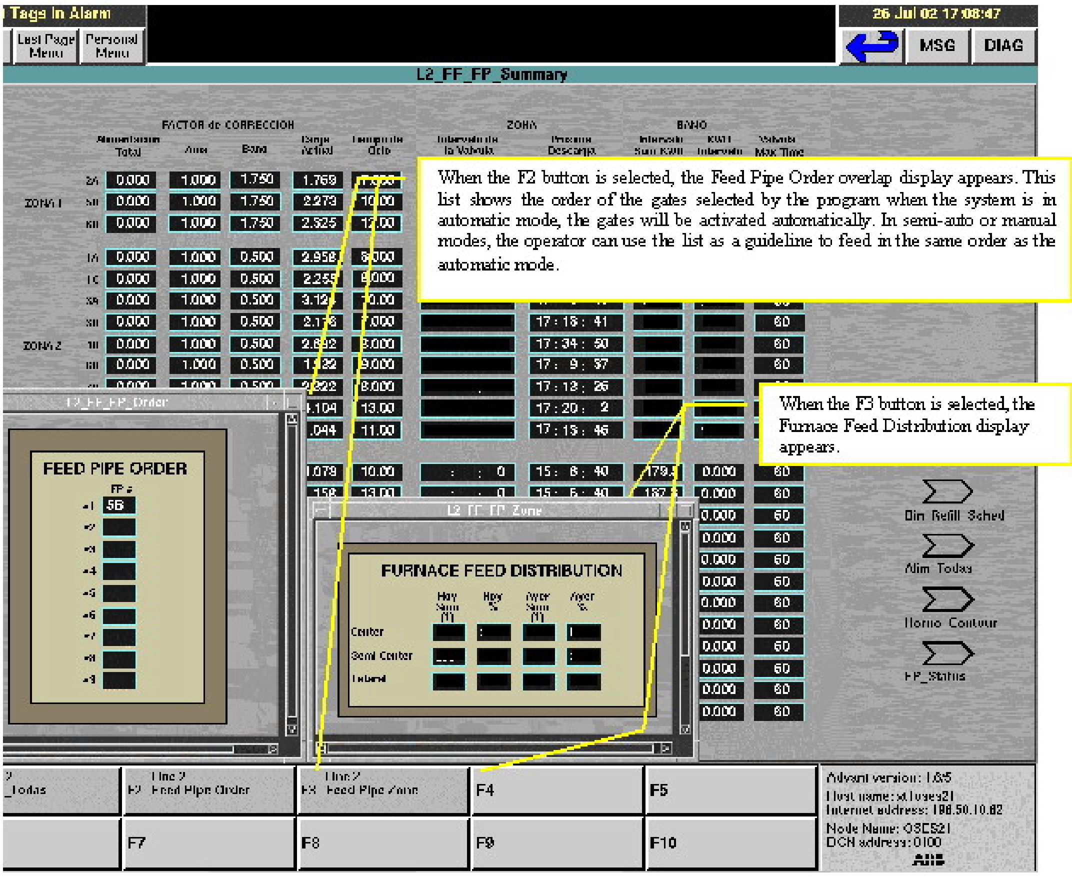

Figure 6. Furnace Feed Controller details Screen for the Line 2 Furnace.

Figure 7 shows a screen capture of the On-line Heat balance screen for the Line 2 Furnace. The labels highlight the trend of estimated smelting efficiency and the trend for estimated shell losses. The bar graph of the estimated metal level in the furnace is also shown. The on-line heat balance provides a clear summary interface for the complex on-line heat balance calculations.

4.3 Furnace Monitoring and On-line Heat Balance

Referring back to Figure 1 describing the covered-arc smelting process, the On-line Heat Balance module tracks the energy losses from the furnace and estimates the metal accumulation in the furnace.

The On-line Heat Balance (OHB) module:

- Displays a computed sidewall heat fluxes and an estimated residual wall thickness calculated from embedded thermocouples
- Provides uncovered arc detection with heat fluxes and temperature from the roof thermocouple measurements
- Provides and estimate of the metal level in the furnace.

The OHB module also collects sensor data to establish and track the furnace net specific energy utilization (energy efficiency) in terms of kWh/t.

- Off-gas heat loss that is assessed by the measurement of temperature, flow and chemistry, from the Off-Gas System.
- Electrical losses are measured from the water temperature difference across the water-cooled bus, and the transformer loss and efficiency
- Electrical power heat source, which is measured electrically on the furnace transformer primary
- Hot calcine heat source. The calcine injection rate is obtained from the Furnace Feed Control System and the calcine temperature is measured by a thermocouple.
- The CO combustion heat source that results from the heat generated by the reaction of CO into CO_2.

Heat from air infiltration and electrode consumption are also accounted for.

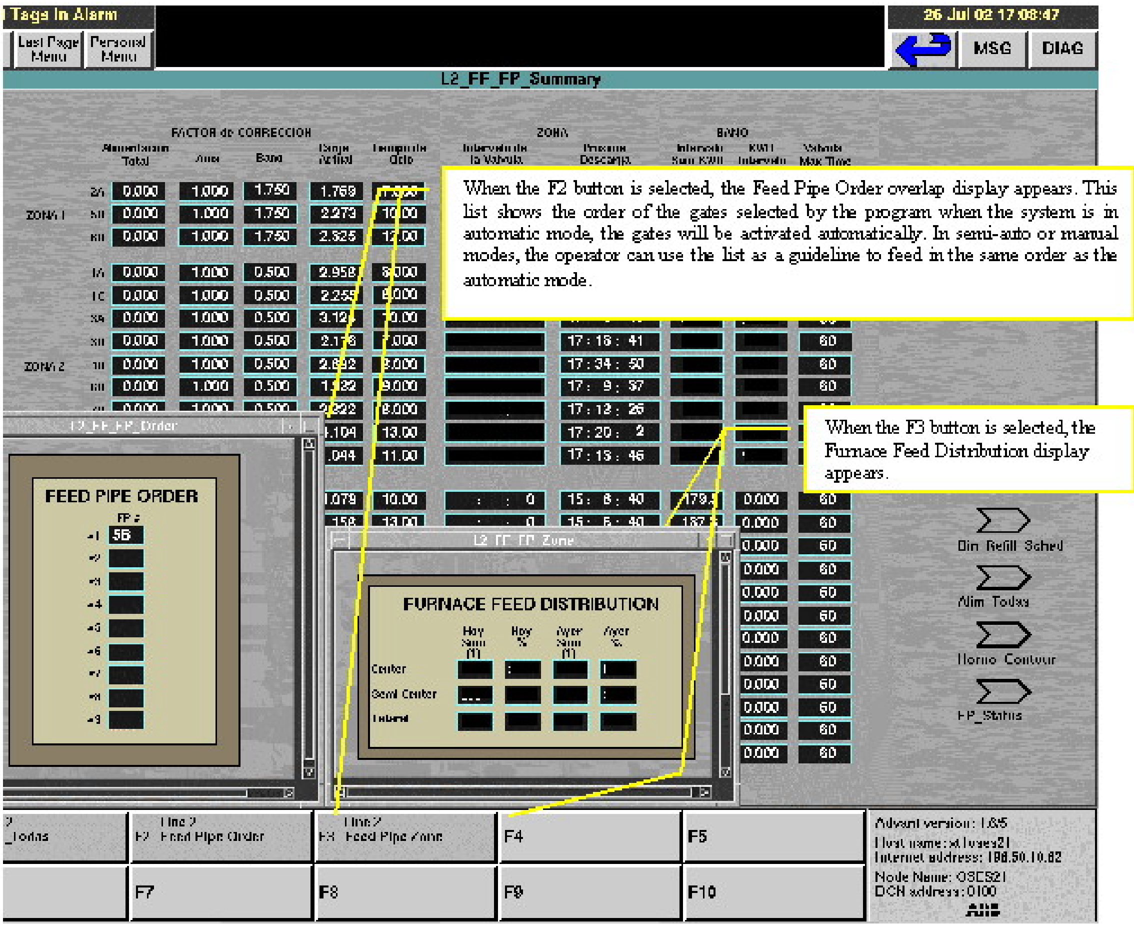

Figure 7. On-line Heat balance Screen from Line 2.

4.4 Furnace Supervisory Controller

The Furnace Supervisory Control Module provides overall control of the furnace and governs the interactions between the various modules of the furnace control system. Specifically the furnace Supervisory Controller system links the Feed Controller, Furance Power Controller and On-line Heat balance using the following equations:

- In *feed rate mode*, feed rate and net specific energy requirement (kWh/t) are used to determine the power set point.
- Power Set point = (Measured Feed Rate x net specific energy requirement) + Power Losses
- In *power setpoint mode*, the measured power (MW), power losses (MW) and the net specific energy requirement (kWh/t) are used to determine the feed rate.

The supervisory control interface for Line 2 Furnace is shown in Figure 8. The notes on Figure 8 highlight the fields that allow the operator to manually enter the power and feed setpoint or enter either power or feed and have the other calculated. An input is also provided to perform ramping between power or feed setpoints.

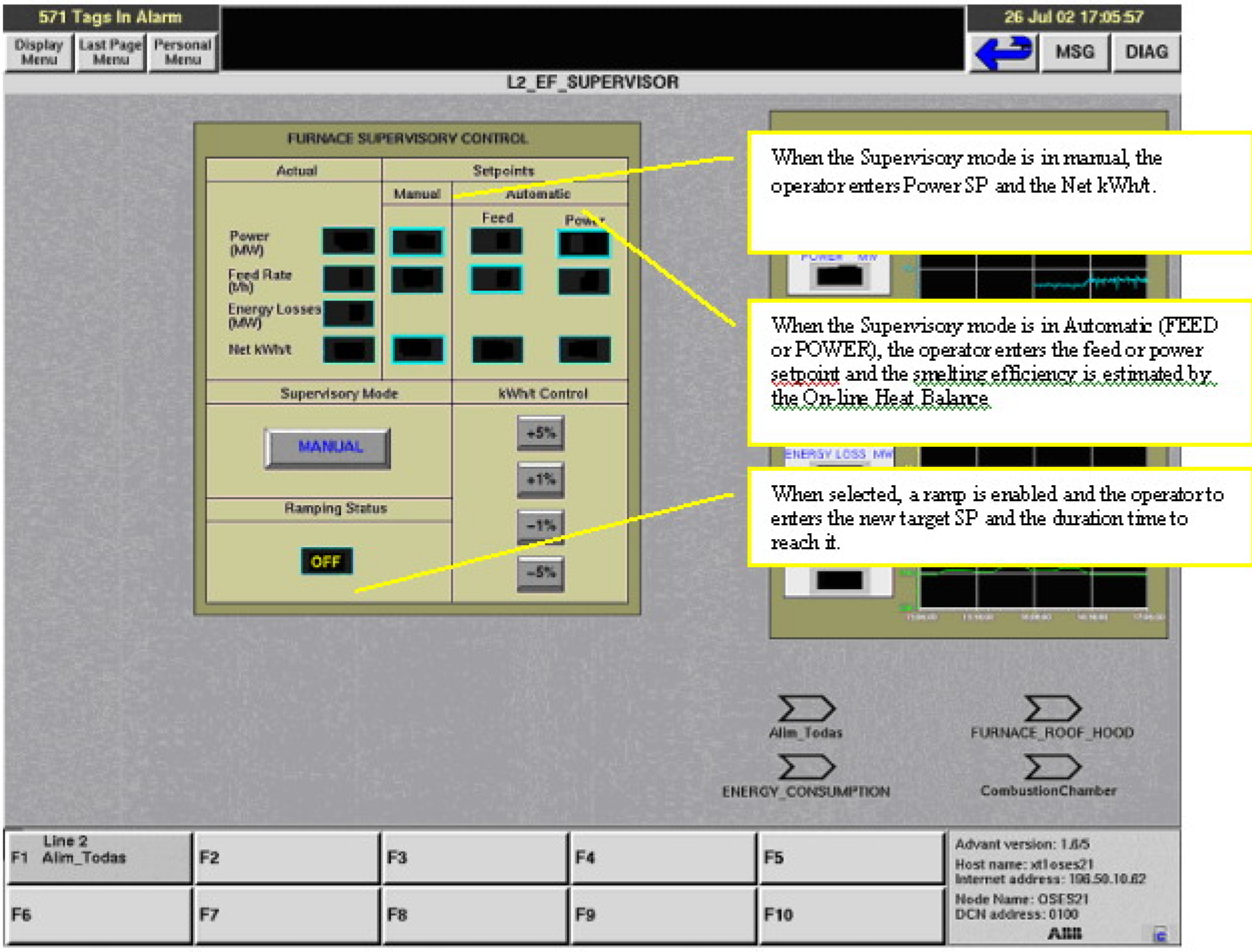

Figure 8. Supervisory Control screen for the Line 2 Furnace.

5. CONCLUSION

An Integrated Furnace Control System is described that has been tailored to the shielded-arc smelting process with examples taken from the recently started Cerro Matoso Line 2 Furnace. The automatic electrode positioning and feeding used on this furnace provides stable operation at the design power level of 75 MW. The Integrated Furnace Control system gives the operators both control and process information. This sophistication has enabled increased power with minimum excursions and upsets, which if not closely controlled could cause rapid damage at high power.

From Figure 1, the Integrated Furnace Control System controls and/or monitors the power, feed, energy, metal and slag entering and leaving the furnace at the boundaries, and provides some insight into the process conditions inside. The next generation of controls being developed by Hatch will embed process models that enhance control during upset conditions and/or automatically bring the furnace back to equilibrium after a substantial upset.

Although this paper describes how the Integrated Furnace Controls were tailored to the shielded-arc smelting process, the concepts have been proven equally effective for other processes including immersed electrode furnaces.

6. ACKNOWLEDGEMENT

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