THE DEVELOPMENT AND APPLICATION OF A HCFeMn FURNACE SIMULATION MODEL FOR ASSMANG LTD

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ABSTRACT

Over the last decade significant development and use has been made of a simulation model that describes the HCFeMn smelting operations in Assmang Ltd. This spreadsheet based, semi-empirical, predictive model is derived from data from the submerged arc furnaces at Assmang's Cato Ridge, KwaZulu-Natal smelter site.

Departures from the empirical base case mass balance due to changes in the ores, reductant feeds and operating parameters are accounted for by use of fundamental relationships and heuristic type ratios which are applied in an iterative manner in the model. The model performs a sequential set of calculations to iteratively converge on a fully consistent mass and energy balance solution, which predicts Mn alloy and slag output masses and compositions for a given set of feeds. 440 MWh per operating day is used as the basis of energy input.

The paper describes the key model components, assumptions made and calculation approach. Added to the mass and energy balance is a cost and revenue balance, which allows prediction of the economic performance for each simulation.

Substantial use of the model has been made in simulating the performance of the current Assmang HCFeMn furnaces for both smelter investigations and future production planning. The model has also been a valuable tool in the strategic analysis of the use of future Mn ores and has formed the vital link between mine ore grades (metal and slag elements) and the expected alloy output, grade and profitability. Additionally, the model has been used in benchmarking exercises to predict other Mn smelting operations with remarkable accuracy. The paper highlights some aspects of the approaches taken in using the model to benchmark Assmang's own furnace performance and cost competitiveness with other producers.

For Assmang the development and application of this modelling technology has led to transformation in understanding of the Assmang HCFeMn furnace operations and increased awareness of the potential of its Mn ore bodies.

1. INTRODUCTION

In the operation of any ore smelter that produces a saleable metal product, the integration of mine ore supply, smelting operations and markets is important for the effectiveness and profitability of the smelting business. At the heart of achieving this integration is the mass/energy balance across the smelter. Over the past years significant progress has been made in the development of models to quantify such balances and describe furnace metal/slag outputs from smelted ore feedstocks. Some of these model tools have been based on fundamental equations governing partition of metal, slag and dust elements, net energy requirements and gas evolution [1], while other models are developed from purely empirical relationships drawn from operational data.

In the production of ferro-alloys, some of these models allow the prediction of metal alloy output and grade from a set of ores of known composition smelted with a given power input to the furnace. Variances in ore mix feed compositions, particularly of the main metal and slag forming constituents, may then be assessed with regard to their influence on alloy grade, slag production, power consumption and importantly also with

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regard to their impact on the economics of saleable alloy production. To achieve this economic assessment, such predictive models must be extended to incorporate costs of the smelting consumables, labour costs and other variable and fixed costs in a cost balance linked to the mass/energy balance. For a given unit alloy revenue price and a unit production cost the net profit margin per unit of alloy may then be predicted for a unique consumption set of ores, reductants, fluxes and power. This extended model now forms the vital connection between mined ores, smelted alloy and market revenue.

For Assmang Limited such a furnace simulation model has been developed. Fundamental relationships describing Mn oxide reduction and slag chemistry are used together with empirical operating furnace data. The operational data are taken from the furnaces in the Assmang Mn smelter works situated near Cato Ridge in the province of KwaZulu-Natal, South Africa.

Figure 1 shows the location of the smelter works site relative to the Assmang Mn mines at Black Rock in the Northern Cape Province of South Africa. Also shown is the port city of Durban from which Assmang's alloy products are shipped.

Figure 1. Location of Assmang's Mn mines and smelters in South Africa.

Table 1 summarises the characteristics of the furnaces and metal produced at Assmang's Mn smelter works. The ores smelted are principally from Assmang's Black Rock mines, namely Nchwaning ore (50.0%Mn, 9.6%Fe) and Gloria ore (38.5 %Mn, 4.8 %Fe). Sweetener ores (high Mn/Fe ratio) are also used, such as imported ore from the Eramet Comilog mine in Gabon (49.6 %Mn, 2.5 %Fe). Sinter using Nchwaning ore and Gloria ore fines was produced at Iscor Newcastle, but currently sinter from Samancor's Mamatwan plant is being smelted in the ore mixes. Reductants used are Coke from Iscor, Zimbabwe or China (approximately 80 – 82 % fixed carbon) and Anthracite (77 % fixed carbon) from KwaZulu-Natal. Quartz and limestone fluxes are sourced locally.

Table 1. Assmang Mn Smelter Works, Cato Ridge – furnace and metal characteristics.

Operating Furnace	**Furnace Type**	**Transformer rating MVA**	**Metal Products**	**Metal Grade %Mn**
1	Partially closed	1 x 22	SiMn or HCFeMn	68 78.5
2	Partially closed	1 x 22	HCFeMn	78.5
3	Closed	1 x 12	HCFeMn	78.5
4	Closed	1 x 12	HCFeMn	78.5
5	Open	3 x 8	HCFeMn	78.5
6	Closed	3 x 8	HCFeMn	78.5

2. FURNACE MODEL DEVELOPMENT

2.1 Overall Furnace Model Structure

To simulate the reduction smelting of Assmang's Mn oxide ores, a simulation model was developed using the Microsoft Excel® spreadsheet software. Overall the model was formulated to predict HCFeMn alloy output mass and grade for a set of feedstocks of known composition and relative mass proportions. A base case mass/energy balance was established using extensive historical data taken from Furnace no. 5.

A furnace model was then developed starting with a mass balance, which involved a complete element balance from inputs to outputs. Using this detailed mass balance a heuristic mass/energy balance was incorporated with an empirically determined equation to predict %MnO in furnace slag. The model was developed to allow deviations or variations from the base case when other ore and reductant mixes are smelted. Ratio's and equations govern the departure from the base case with constants taken from the base case data set. The overall computational sequence and basis is described below using the mass streams defined for Assmang's HCFeMn furnace operation, as shown in Figure 2.

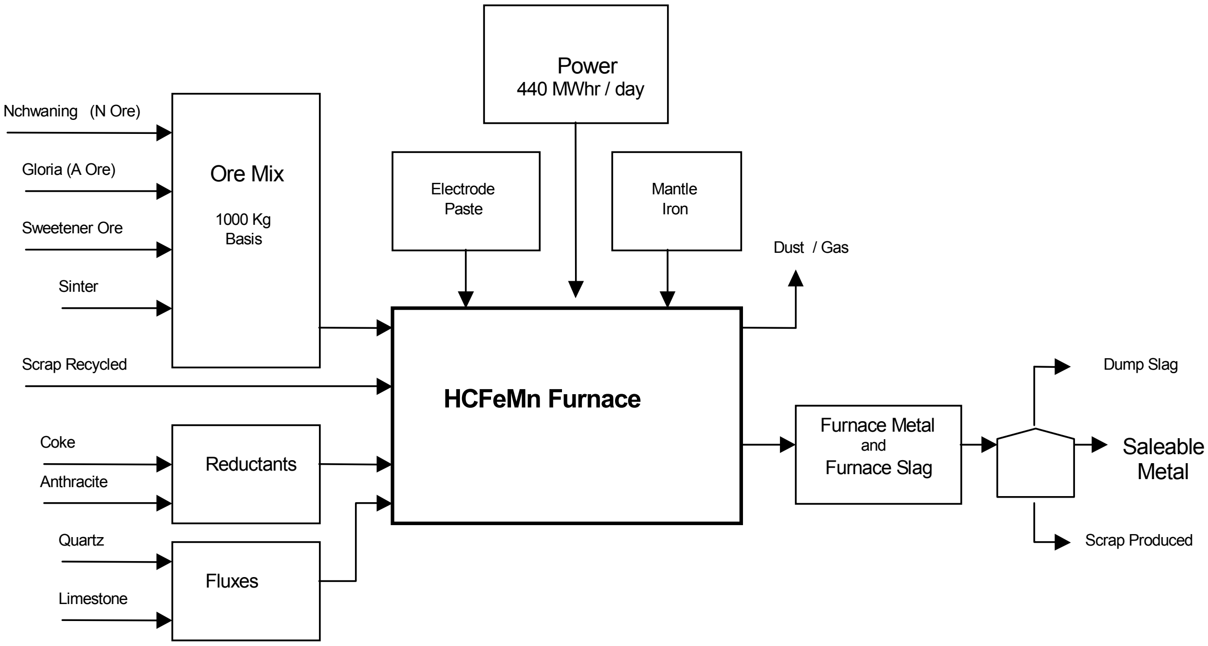

Figure 2. Furnace Model mass flow streams for Assmang's HCFeMn furnaces.

For a 1000 Kg of Ore Mix with known ratios of the ore types used, namely Nchwaning (N ore), Gloria (A ore), Sweetener ore and Sinter, together with related inputs of Reductants, Fluxes, and Electrode Paste, the masses of slag forming components CaO, SiO_2 , MgO and Al_2O_3 are calculated. A 100% deportment to slag of these oxides is assumed, apart from those oxides reporting to Dust and a small amount of Silicon into the Furnace Metal. The Furnace Model uses a relationship to determine the Reductants consumption per tonne Ore Mix (see equation 3) with the consumption of Fluxes and Electrode Paste as given inputs. These slag components plus an assumed % Other in slag (see equation 2 in section 2.2.2) and a calculated %MnO in slag (see equation 1 in section 2.2.1) are used to iteratively converge on a solution for the composition and mass of the Furnace Slag. With the mass of Mn then known in Furnace Slag, the Mn in Furnace Metal is calculated by difference from total Mn input in the Ore Mix, Reductants, Scrap Recycled and Electode Paste, less the Mn in the Dust.

The Fe mass in Furnace Metal is calculated from all Fe inputs into the furnace (including Mantle Iron) less the Fe units in the Dust. The other elements in the Furnace Metal, namely C, P, Si and S are provided as input parameters. Therefore, with the Mn and Fe masses in Furnace Metal known per 1000 Kg of Ore Mix, the mass of Furnace Metal may be solved whose solution is by iterative convergence with the solution to the slag balance.

The Furnace Model predicts the masses of Saleable Metal and Dump Slag produced by completing a balance using the “loss” stream of Scrap Produced per tonne Ore Mix, a given input parameter. Scrap Produced is assumed to comprise both Furnace Slag and Furnace Metal. Refer to section 2.2.5 for a discussion on the handling of scrap.

In order to estimate what tonnage of Ore Mix can be smelted per day and therefore what Saleable Metal per day is produced, a base case was established using reliable operational data from Furnace no. 5 treating an Ore Mix of 80% Gloria and 20% Nchwaning ores. The Furnace Model employs an ore consumption equation (equation 5) involving constants to describe daily Ore Mix consumption and daily Furnace Slag and Furnace Metal production. These constants are fixed by the empirical data of this base case. This ore consumption equation also includes constants which take into account, inter alia, the major net endothermic reduction reactions, heats of formation and sensible heats involved in HCFeMn metal and slag smelting. Departures from this base case mass/energy balance, in smelting a new Ore Mix with different consumptions of Fluxes and Reductants, are accounted for in this equation via heuristic type ratios relative to the constants set by the base case. The energy balance captured in this ore consumption equation is solved iteratively in conjunction with the mass balance. Refer to discussion in section 2.2.4 on ore consumption.

The power input per day for the base case was established as 440 MWh/d which represented the average power consumed per day on Furnace no. 5 with no downtime. This block of power input on which the Furnace Model’s mass/energy balance is based may be seen as a “unit” of power consumed by a furnace. Multiples of this unit of power can then be applied to larger or smaller furnaces, taking account of different furnace heat loss characteristics where necessary, to determine the outputs of metal and slag from those furnaces.

2.2 Furnace Model Components

2.2.1 MnO in slag

At the heart of the Furnace Model is an estimation of the %MnO in slag given by a regression model for the prediction of %MnO in slag, shown by equation 1. This equation is a linear regression model based on average monthly data from four furnaces at Assmang Mn smelters at Cato Ridge, and is of the form:

$$\%MnO\ in\ slag = 77.92 - 1.369 * (\%CaO + \%MgO) \qquad (1)$$

where: %MnO in slag is the mass % of MnO in Furnace Slag
%CaO in slag is the mass % of CaO in Furnace Slag
%MgO in slag is the mass % of MgO in Furnace Slag

The regression in equation 1 gave an r^2 of 0.921 with a standard error of 0.77%. The data used covered a relatively wide range of %MnO in slag (19.6% – 29.9%) and of slag basicity (1.22 – 1.35).

Figure 3 shows the predicted %MnO in slag versus actual %MnO in slag, and indicates the ability of equation 1 to describe MnO content in slags of the Assmang furnaces. It should be noted that the data used to develop equation 1 covered periods in which varying proportions of ores (N and A), Sweetener and Sinter were smelted in the furnaces and therefore equation 1 covers a fairly wide range of furnace slag chemistry.

In equation 1, the choice of the sum of the variables %CaO and %MgO versus that of slag basicity (%CaO+%MgO)/%SiO_2 to describe %MnO in slag, is strongly supported by the slag data plotted in Figure 4. Figure 4 shows the strong dependence of MnO in slag on the alkali earths CaO and MgO, with a rather weak dependence on basicity itself. The data confirm that by increasing the concentration (mass %) of CaO and MgO the activity of MnO in slag is increased which enhances the reduction of MnO from the slag as Mn into the metal. Although the general trend of decreasing MnO in slag with increasing basicity has been reported for aluminate slags [2], regression work on Assmang’s furnace data using basicity as a variable to describe MnO in slag did not support its use. The Furnace Model therefore uses equation 1 to determine MnO in slag and is solved iteratively in the mass/ energy balance.

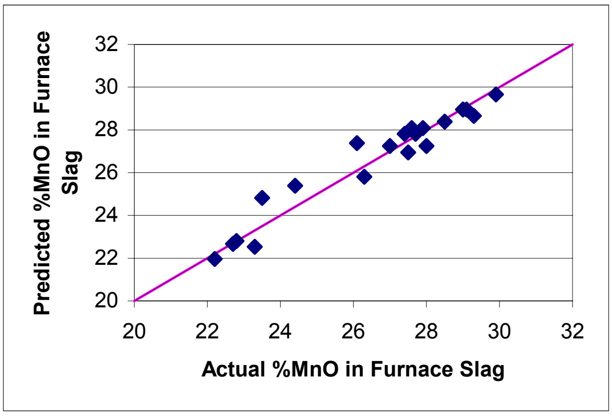

Figure 3. Actual vs. Predicted %MnO in Furnace Slag.

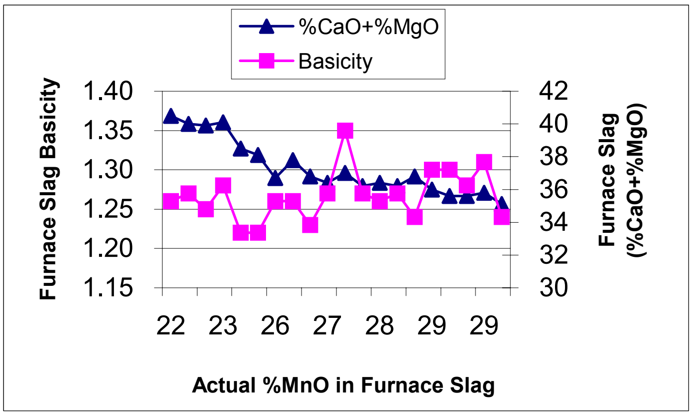

Figure 4. Furnace Slag %MnO vs. Basicity and Furnace Slag %CaO+%MgO.

2.2.2 % Other in slag

In defining the mass balance over the slag, a fraction of the slag was determined to represent all other components in the slag other than CaO, MgO, SiO_2 and MnO. The % Other in slag is defined in equation 2:

$$\%\ Other\ in\ slag = \%Al_2O_3 + \%BaO + \%FeO + Other\ unknown\ components \qquad (2)$$

where: % Other in slag is the mass % of other components in Furnace Slag
$\%Al_2O_3$ in slag is the mass fraction of Al_2O_3 in Furnace Slag
%BaO in slag is the mass fraction of BaO in Furnace Slag
%FeO in slag is the mass fraction of FeO in Furnace Slag

Other unknown components represent any other metal oxides and any non-stochiometric oxygen in the slag not accounted for by the stochiometry of the oxides given in equations 1 and 2.

Inclusion of this % Other in slag term in the slag balance allows the Furnace Model to more accurately predict the mass of Furnace Slag, but requires an estimate of this fraction for slags resulting from a given set of furnace feeds. Composition measurements of the slags at Assmang show that the % Other in slag varies from 5.2% to 8.1% for slags whose MnO content is described by equation 1. Further development of the Furnace Model allowed calculation of the $\%Al_2O_3$ in the slag. Al_2O_3 is calculated by all known Al_2O_3 masses in the feeds reporting to both the slag and dust. The mass % of FeO is given as an input parameter (typically 0.2%) depending on the smelting operation and degree of reduction. By difference from the estimated or measured % Other in slag the remaining mass % of BaO and other unknown components is calculated. From Equation 2 solved iteratively with Equation 1, all of the slag oxides are computed by the model and all unknown components given a mass to fully complete the slag mass balance.

It has been shown that the magnitude of % Other in slag has a significant effect on the other major components of the same slag, i.e. CaO, MgO, SiO_2 and MnO, and hence on the overall iterative solution to the mass/energy balance. Simulation work done on Assmang's slags has shown that at a given basicity, the % MnO in slag is not constant but a complex function of the reduction potential of the slag, slag basicity and the % Other in slag. The Furnace Model caters in part for this complexity by inclusion of this % Other in slag term.

2.2.3 Reductant consumption

Part of the iterative solution to the furnace mass/energy balance is the prediction of Reductants usage per ton of Ore Mix. This prediction is important in the Furnace Model not only to describe the consumption of reductants (coke and/or anthracite) resulting from the reduction smelting of a particular Ore Mix, but also to quantify the slag components and metal elements introduced into the furnace by these reductants.

The Reductants usage equation used in the Furnace Model is given by:

$$Z = a + (b * X) / (k * y) - (X - 161.08) * 0.14 * (12/56) / (k * y) * 1000 \qquad (3)$$

where: Z is the Reductants usage (wet) in kg/tonne Ore Mix
a is an empirical constant, currently zero kg/tonne
b is an empirical value set at 342 kg fixed carbon/tonne Furnace Metal
X is the Furnace Metal production in tonnes/day
k = (fc*dm) with fc as the weighted mass fraction of fixed carbon in Coke and/or Anthracite making up the reductant mix, and dm the weighted mass fraction of dry reductant mix per mass wet reductant mix
y is the Ore Mix fed to the furnace in tonnes/day
161.08 is the average Furnace Metal production in tonnes/day for the base case

Equation 3 was developed for the base case mass balance in which an empirically determined value of 342 kg fixed carbon was required for the base case production of 161.08 t/d Furnace Metal. The second term in equation 3 is a correction term which estimates the amount of carbon required in the reduction of the iron (approximately 14%) contained in the differential Furnace Metal production per day above or below the base case production of 161.08 t/d. The equivalent reductants wet mass/tonne Ore Mix is calculated to give this carbon and subtracted from the base case Reductants usage per tonne Ore Mix. This correction term is necessary as some of the CO gas evolved in the final reduction of MnO in slag to Mn in Furnace Metal is used again in the reduction of iron oxide.

To account for the observed decreases in Reductants usage resulting from the use of sinter in an Ore Mix, equation 3 was modified to cater for Sinter in the Ore Mix. Gericke [3] reported a decrease in reductant usage of 4.7% at 36% sinter in the ore mix when smelted in Samancor's South African furnaces. A ratio of this decrease is applied to adjust the Reductants usage per tonne of Ore Mix in equation 3, shown in equation 4, as follows:

$$Z(s) = Z * (1 - j / \mathrm{m} * \mathrm{n}) \qquad (4)$$

where: Z(s) is the Reductants usage (wet) in kg/tonne Ore Mix when the Ore Mix contains sinter Z is as defined in equation 3
j is the % by mass of sinter in the Ore Mix
m =36%
n is the fractional decrease in Reductants usage, currently set at 0.047

2.2.4 Ore Mix consumption

To determine the tonnage of Ore Mix fed to a furnace to satisfy 440 MWh/d an Ore Mix consumption equation was developed and is solved iteratively within the mass/energy balance of the Furnace Model. The Ore Mix consumption equation is of the following form:

$$\mathrm{W} = \mathrm{c} - \mathrm{d} * X_1 - X_2 - \mathrm{e} * X_3 - (X_4 - \mathrm{f}) * \mathrm{g} / X_5 + (\mathrm{h} - X_6) * \mathrm{i} / X_6 \qquad (5)$$

where: W is the tonnage of an Ore Mix (wet) which excludes sinter fed to the furnace per day
X_1 = Quartz flux added in tonnes/day
X_2 = Limestone flux added in tonnes /day
X_3 = Scrap Recycled in tonnes/day
X_4 = Furnace Metal produced in tonnes/day
X_5 = Furnace power input in MWh/tonne Ore Mix
X_6 = Furnace Slag produced in tonnes/day

With constants:

c = a constant characteristic of the furnace, set at 392 Ore Mix tonnes/day derived for the base case
d = estimate of the relative energy consumption of Quartz compared to Ore Mix, set at 0.5
e = estimate of the relative energy consumption of Scrap Recycled compared to Ore Mix, set at 0.7
f = base case Furnace Metal production estimated at 161.08 tonnes/day
g = net reduction, metal sensible heat and metal heat of formation energy (including vaporisation energy), estimated at 1.1659 MWh/t Furnace Metal. (from reference [4])
h = base case Furnace Slag production estimated at 162.86 tonnes/day
i = net slag sensible heat and heat of formation energy estimated at 0.2963 MWh/t Furnace Slag

When sinter is included in the furnace Ore Mix a modification is made to equation 5 to improve the estimate of the tonnage of Ore Mix consumed per day for an energy input of 440 MWh. This modification accounts for the loss to the furnace of the exothermic energy released during sintering on reduction of primarily the first Mn oxide MnO_2 in the ore. The relevant overall reaction to consider is:

$$CO + MnO_2 \rightarrow MnO + CO_2 \qquad (6)$$

For this reaction ΔH equals -35100 calories per mole of MnO_2 [5] and assuming 13.2% Mn is present as MnO_2 equivalent in Gloria type ore then the exothermic energy lost to the furnace per tonne of sinter is estimated to be 116.7 kWh/t sinter. This energy is assumed to be replaced by electrical energy and therefore for a fixed energy input into the furnace of 440 MWh/d the Furnace Model corrects downward the tonnage of Ore Mix (including sinter) that can be smelted. This gives equation 7, as follows:

$$W(s) = W - (j * X_7 * k/100 * X_7 / l) * r \qquad (7)$$

where: W(s) is the tonnage of Ore Mix (wet) which includes sinter fed to the furnace per day
W as defined in equation 5
X_7 = the previous iteration value for Ore Mix (including sinter) fed to the furnace per day
j = the % by mass of sinter in the Ore Mix
k = exothermic energy lost to the furnace, set at 0.1167 MWh/t sinter
l = 440 MWh/d energy input into the furnace
r = fractional upward correction factor to cater for a residual amount of MnO_2 left in the sinter

From reported operations at SEAS in France [6] residual MnO_2 occurs in sinters as some of the MnO_2 is unreduced during the sintering process. Therefore the correction factor r was introduced into equation 7 to cater for the energy credit that this unreduced Mn oxide brings to the smelting process.

2.2.5 Handling of scrap

The Furnace Model caters for the smelting of scrap materials fed to the furnace as Scrap Recycled. Scrap materials arise from launder and ladle skulls, Furnace Metal splashings, dusts and spillage on tapping, teaming and casting. The amount of Scrap Recycled is a given input into the model as kg Scrap Recycled/tonne Ore Mix. In equation 5 the relative energy consumption of Scrap Recycled to that of Ore Mix is set at 0.7. Hence for every 1 tonne of Scrap Recycled to the furnace, 0.7 tonnes less Ore Mix may be smelted. Therefore this equivalent tonnage of Ore Mix is subtracted from the base case Ore Mix tonnage smelted using 440 MWh/d.

In Figure 2, the production of scrap is schematically represented as a loss stream from Furnace Metal to Saleable Metal.

In the Furnace Model this stream as Scrap Produced caters for all the losses of Furnace Metal described above as well metal fines losses in the HCFeMn alloy crushing and screening plant. Saleable Metal is defined for the Assmang furnaces as lumpy and fines products weighed, stockpiled and dispatched for sale.

For the Furnace Model the Scrap Produced is given an estimate in kg/tonne Ore Mix based on past estimates of the Scrap Produced that was largely all recycled. However, smelting practices today avoid large recycle of scrap materials and seek to minimize scrap materials produced, in order to maximize saleable metal per unit of power input or per unit of ore smelted.

2.2.6 Furnace Metal composition

A summary of typical composition elements predicted for Furnace Metal is shown in Table 2, with comment on the model output or requirements for computing each element.

Table 2. Furnace Model predicted metal composition.

Furnace Metal Element	**Furnace Model Predicted %**	**Furnace Model Output / Requirement**
Mn	79.202	Solved by iterative calculation
Fe	13.573	Solved by iterative calculation
C	7.100	Given input , at 7.1% Carbon in HCFeMn
Si	0.050	Given input, typically 0.05% Silicon in HCFeMn
S	0.004	Calculated from S inputs, assuming recovery of S to Furnace Metal of 1.5%
P	0.071	Calculated from P inputs, assuming recovery of P to Furnace Metal of 85%

2.2.7 Other Furnace Model inputs

The Furnace Model requires some other input parameters that are summarised below in Table 3.

Table 3. Other Furnace Model input parameters.

Furnace Model Parameter	**Description**
Fluxes: Quartz Limestone	Given input consumption, kg/tonne Ore Mix, with known composition Given input consumption, kg/tonne Ore Mix, with known composition
Electrode Paste	Given input consumption, kg/tonne Ore Mix, with known composition
Mantle Iron	Calculated via given input of electrode slip, mm/tonne Ore Mix, with assumed geometry of mantle casing, fins. Typically 5 mm/tonne Ore Mix
Dust Produced	Production of dust from assumed % of all solid feeds to furnace, Ore Mix, Scrap Recycled, Paste , Fluxes, Reductants and Mantle Iron. Typically 2.3% with given input composition of dust
Furnace Model Mass Balance Elements used where applicable	Mn, Fe, SiO_2, CaO, MgO, Al_2O_3, P, S, Si, C, H_2O and % Ash and fixed carbon in Reductants

3. FURNACE MODEL APPLICATIONS

3.1 Prediction of Assmang furnace performance

To indicate the validity of the Furnace Model in adequately predicting the performance of the Assmang's HCFeMn furnaces, average monthly data were used in the simulation of the smelting operation. Five separate months of operation on Furnace 5 were considered, in which ore mixes containing various levels of sinter were smelted. Table 4 shows some of the key parameters simulated by the Furnace Model, which are compared against actual values.

For each month no accurate mass measurements were recorded of the Scrap Produced from the Furnace Metal output. Only the Saleable Metal tonnage produced was available. Therefore, in each month's simulation the Scrap Produced (kg/tonne Ore Mix) was varied to allow the simulated value of MWh/t Saleable Metal to equal the actual value, given the Furnace Model's set unit input of energy of 440 MWh per operating day. With the average Ore Mix components and their respective compostions known, as well known measurements of % Other in slag, the furnace performance was simulated and the key variable of Ore Mix consumption with the compositions of Furnace Metal and Furnace Slag predicted, as shown in Table 4.

From Table 4, the Furnace Model is shown clearly to adequately predict the performance of Assmang's HCFeMn furnace operation from the data used. Good levels of accuracy are achieved in prediction of Ore Mix consumption, with an absolute % variation from actual values of 0.3% to 3.5%.

The key parameter of predicted %MnO in slag differs in absolute terms from the actual %MnO in slag by on average 6% (1.5% to 11.2%). This deviation may largely be due to the unexplained variance in the MnO in slag model used in the Furnace Model, given by equation 1, This regression equation has a r^2 of 0.921 which means that the regression model does not explain 7.9% of the variance of the data used in the regression. Note that the range of %MnO in slag values in Table 4 does fall in the range described by the regression model in equation 1. Although in these simulations the MnO in slag predictions show relatively significant variances from the actual data, the full slag composition with respect to SiO_2, CaO and MgO are well predicted and are accurately solved for in the mass/energy balance of the Furnace Model.

Table 4. Furnace Model prediction of Assmang's HCFeMn Furnace 5 performance.

Month	**% Sinter in Ore Mix**		**Saleable Metal tonne per day**	**Ore Mix tonne per tonne Saleable Metal**	**Furnace Metal Composition**		**Furnace Slag Composition**				
					Mn %	**Fe %**	**MnO %**	**SiO_2 %**	**CaO %**	**MgO %**	**% Other in Slag**
1	**0**	**Actual**	164.8	2.089	79.1	13.2	26.3	30.0	29.8	8.0	5.9
		Predicted	164.8	2.162	79.3	13.5	25.9	30.2	30.2	7.8	5.9
2	**0**	**Actual**	161.3	2.263	79.0	13.5	28.1	29.2	28.9	7.3	5.5
		Predicted	161.3	2.270	79.1	13.7	26.1	30.5	30.2	7.6	5.5
3	**16.8**	**Actual**	165.3	2.320	78.9	13.7	27.7	29.0	28.3	7.6	6.8
		Predicted	165.3	2.291	79.1	13.7	28.9	28.5	28.4	7.3	6.8
4	**15.3**	**Actual**	158.3	2.391	78.8	13.7	27.6	28.6	29.1	7.0	7.6
		Predicted	158.3	2.417	78.6	14.2	30.7	27.2	27.5	7.1	7.6
5	**9.0**	**Actual**	155.7	2.451	78.8	13.8	29.3	27.3	29.1	6.7	7.6
		Predicted	155.7	2.466	79.2	13.6	27.6	28.0	29.9	6.9	7.6

Equally from Table 4, it may be noted that the Furnace Model predicts accurately the Furnace Metal composition with respect to Mn and Fe content. In these simulations an absolute % variation from actual values of less than 1% is achieved in predicting %Mn in Furnace Metal and less than 4% for %Fe in Furnace Metal. This accuracy shows the reliability of the Furnace Model to solve the Furnace Metal mass balance in the overall iterative mass/energy balance structure of the Furnace Model.

3.1.1 Effect of sinter

The example data in Table 4, for month 3, shows the slight benefit of using sinter in the furnace for an Ore Mix containing only 16.8% sinter. Extensive trials however, have been conducted on the Assmang furnaces to investigate the benefits of using sinter in the Ore Mix at levels of up to 60%. Actual data from these furnace trials over a period of 7 years have been collected and were examined. From analysis of the average monthly plant data a benefit of 0.130 MWh/t saleable metal was seen in the use of sinter when moving from a 20% to a 50% usage level in the Ore Mix. The actual data were also explored using multiple linear regression techniques and a model developed which predicted a benefit of 0.145 MWh/t Saleable Metal in going from 20% to 50% sinter [7]. The regression model shown in equation 8 gave an r^2 of 0.864, i.e. describes 86.4% of the variance in Saleable Metal production for the range of data considered. The regression model is of the general form:

$$S = p + q * (\%\ Sinter) + F \quad (8)$$

where: S = Saleable Metal production in tonne/day
p = a regression constant
q = regression coefficient of the variable % Sinter, determined as 0.26
% Sinter is the mass percentage of Gloria ore sinter in the Ore Mix
F is the remaining regression function with coefficients and associated variables of % Utility, % Furnace Availability, % Anthracite in Reductants, % Sweetener in Ore Mix and % MnO in slag.

The coefficient q's positive value of 0.26 shows the benefit of increasing sinter on increasing Saleable Metal production. To confirm this benefit the average monthly data were used in the Furnace Model and the benefit of increasing sinter from 20% to 50% in the Assmang furnace Ore Mix was simulated. In Table 5, the benefit is expressed as a decrease in furnace energy consumption and the simulation result is compared to those from the actual plant data and to the output of the multiple linear regression model, described in equation 8. From Table 5 the simulation result from the Furnace Model is acceptably close to the actual results and confirms the validity of the model to simulate the smelting of Ore Mixes containing sinter.

Table 5. Reduction in MWh/t Saleable Metal due to increasing Sinter from 20% to 50% in Assmang's Ore Mix.

Average Actual Data MWh/t Saleable Metal	**Linear Regression Model MWh/t Saleable Metal**	**Furnace Model Prediction MWh/t Saleable Metal**
0.130	0.145	0.140

3.1.2 Operational considerations in use of the Furnace Model

Although the Furnace Model has been developed and proven to be a powerful and reliable tool in predicting HCFeMn furnace performance for Assmang, particular furnace operational practices and process phenomena are not catered for and cannot be described by the model.

A number of these are briefly discussed here:

- Higher levels of reductant addition to the Assmang furnaces have at times been practised to reduce the level of MnO in the slag, under a basic slag operation. The resultant lower MnO levels (18% – 20% typically) would be predicted by the Furnace Model to give additional Furnace Metal production with more Mn units reporting to the metal. However, in practice, reduced Furnace Metal output has occurred, mainly due to an over-coked furnace condition in which the electrodes tend to pull out of the furnace with the decrease in burden resistance. This has resulted in higher electrode current settings and a decrease in power input to the furnace with lower metal production. Supporting this in equation 8, the function F, has the regression coefficient for the variable %MnO in slag appearing positive which confirms from the plant data that a decrease in MnO in slag actually decreases metal production, for the reasons given above. The Furnace Model does not cater for such electrode penetration operating conditions in the furnace with resulting decreased metal production.
- In the Furnace Model higher levels of % anthracite in the Reductants fed to the furnace are predicted to result in slightly higher Furnace Metal output for a given set of furnace ore feeds, slag basicity and metal grade. However, in practice the higher levels of anthracite, although cheaper when compared to the cost of coke, result in slightly lower Furnace Metal production. Here the cause is likely to be the lower reactivity and effectiveness of anthracite as a reductant comparative to coke. It also seems that higher levels of anthracite in the reductant mix lead to reduced average power input, thereby reducing metal production. The regression model in equation 8 contains a negative coefficient for this variable in function F and shows this lower production result from the plant data considered. The empirical base case used in the the Furnace Model is based on data for Reductants containing only coke. An improvement to the Furnace Model would be the inclusion of a suitable term to adjust Furnace Metal production for the use of anthracite.

- The Furnace Model in its current form does not describe the furnace gas stream and the gaseous species contained in the offgas of the furnace. This gas stream is inherently assumed in the empirical base case and was not specified nor was required to complete the mass/energy balance, as described above in the paper. However, clearly, simulation of the offgas stream would be a significant addition to the Furnace Model and if adequately modelled this could be effectively used to describe the offgas composition from each Ore Mix smelted.

The considerations presented above show that use of a semi-empirical model, such as this Furnace Model, needs to be made with care and due attention to the operational conditions of the HCFeMn furnace, the nature of the feedstocks being smelted and the range of data used as inputs. Although the Furnace Model has definite limitations which require clear understanding, it has been developed into a useful working model for Assmang Ltd.

3.2 Furnace Model cost / revenue balance

Given the Furnace Model's mass/energy balance solution for the smelting of a specific Ore Mix and its prediction of Saleable Metal production per day, a cost and revenue balance was readily applied to calculate the net profit per tonne Saleable Metal for the input set of furnace feeds and compositions.

To complete this cost/revenue balance for each simulation the Furnace Model requires the following input costs:

- Delivered cost per tonne of Assmang ores, sinter, coke, anthracite, limestone and quartz.
- Delivered or on site unit costs of electrode paste and mantles.
- Internal handling cost per tonne of scrap produced and recycled.
- Electrical energy cost per kWh, which includes utility contract fixed charges.
- Estimated other variable costs expressed per tonne saleable metal, to account for other consumables, stores, laboratory and site costs. Also included is the cost of crushing and screening of furnace metal, weighing, storage and rail loading cost per tonne saleable metal.
- Plant overhead cost per day, which includes labour and management costs, applied proportionately for a production energy input of 440 MWh/d.

Selling expenses are defined as a % of gross revenue per tonne Saleable Metal and include marketing costs, agents fees and other contract costs. In order to determine the FOB cost (free on board) or CIF cost (delivered) the relevant transport costs, wharfage fees, port and other charges are applied and added to the selling expenses. From a gross revenue per tonne Saleable Metal assumed for the particular Mn grade of alloy simulated, the total production costs and total selling expenses are subtracted to estimate the net profit per tonne Saleable Metal.

This estimate of net profitability is therefore an integral output of the Furnace Model linked directly to the mass/energy balance solution of each simulation and is specific to the set of ore feeds used in the model.

This capability is a powerful extension of the Furnace Model and has been used extensively to assess:

- Current furnace performance and profitability using particular ores, reductants and power at specific costs.
- Life of operations planning for the Assmang smelter works.
- Future selection, use and profitability of new Assmang Mn ores.
- Feasibility studies on upgraded or new furnace capacity for Assmang.
- Cost competitiveness and benchmarking with other producers.

3.3 Approaches to benchmarking and cost competitiveness

Significant use of the Furnace Model has been made to simulate the HCFeMn furnace operations of other producers. Published and known information from these producers has been used together with reasonable assumptions to predict furnace outputs and benchmark Assmang's own furnace operations. Additionally, for the other producers, the predicted mass/energy balances were used to estimate their cost performance and net profitability. This has allowed Assmang to assess its own cost competitiveness and identify areas for improvement.

Some approaches taken and additional key factors introduced into the Furnace Model to successfully model the furnace operations of other producers were:

- Combination of multiple ore feed types into single weighted streams.
- Direct input of variables as fixed constants, e.g. %MnO in slag, or alteration of the slope, or intercept of the %MnO in slag model in equation 1, as required to give reasonable prediction of slag composition.
- Application of an ore consumption factor, multiplied by the ore consumption model in equation 7, to converge on known ore consumption per tonne values.
- Application of a Reductants usage factor, multiplied by the Reductants usage model in equation 3, to converge not only on known reductants usage levels, but to describe highly reducing, low MnO in slag operations.
- Use of the magnitude of the Scrap Produced stream to calculate known or estimated saleable metal production, and to describe operations with low levels of scrap generation due to bi-level tapping, short launders or direct casting.
- Continued use of the 440 MWh energy input quantum, multiples of which were applied to calculate the actual daily production of metal and slag.
- Given the above approaches and factors applied, remarkable accuracy was achieved in simulating the metal and slag tonnages and compositions of other producers. In these exercises the Furnace Model has proven to be a fairly robust mass/energy framework in which to simulate other HCFeMn furnace operations.

4. CONCLUSIONS

A reliable and relatively robust mass/energy balance has been developed to describe the HCFeMn smelting operation of the furnaces at the Mn Division of Assmang Limited. This semi-empirical furnace model has been successfully developed using a base case mass/energy balance with ratios and relationships applied to cater for departures from this base case. Within the iterative solution the model converges on a complete mass and energy solution to predict the furnace outputs of metal and slag given a unique set of furnace inputs. Accurate simulation of furnace operations using actual plant data has confirmed the validity of the furnace model.

This simulation model tool has allowed the prediction of furnace performance from current ores and enabled Assmang to examine the potential of its future ore bodies. Additionally, the application of a cost/revenue balance linked to the furnace model has enabled the net profitability of current and future furnace operations at Assmang to be explored. Assmang's furnace production and cost performance has also been usefully benchmarked to other HCFeMn alloy producers by using the furnace model.

5. ACKNOWLEDGEMENT

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