Development of a control strategy for the open slag bath furnaces at Highveld Steel and Vanadium Corporation Ltd.

by

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Abstract

This project was the first step in developing a control system for the open slag bath furnace at Highveld Steel, in order to maximize production levels and product quality. In this dissertation, available knowledge from literature and practical experience is included. This is then processed to propose a realistic control system with the current resources available at Highveld Steel.

Through research and practical experience it is shown that these furnaces are extremely sensitive to raw material quality and consistency of decision making. This is a result of the open bath configuration that necessitates the careful control of the excess energy, and the raw material composition supplied to the furnace. Through this project it was shown that both the productivity and the product quality (vanadium recovery) can be increased by simply controlling the feed-to-power ratio and correct use of correction material. This has the effect of stabilizing the process energy balance which results in smaller slag temperature variations and therefore also less product quality variability. Through controlling the feed-power-ratio, energy consumption was also shown to be reduced, since excess power is minimized without negatively impacting on productivity.

In this project a proposal is made to control the flow of material between the two stages in the process, which is based on either being kiln or furnace constrained. A better tapping scheduling is also proposed, based on both material accumulations inside the furnace and the charging condition of the furnace. This results in having sufficient pressure to tap iron and slag at good rates and should also yield consistent tapping weights and add to general process stability.

However, engineering availability strongly impacts on both process control and furnace productivity. Consistent availability of the furnace and its supporting systems is hence essential for optimal operation.

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1. Introduction

Highveld steel and Vanadium Corporation uses a magnetite ore type which is rich in vanadium and titanium. This specific composition was the reason for the process flow diagram, developed in the early 1960s, which is still applied. In 1949 Dr W. Bleloch showed that Bushveld magnetite ore can be melted in submerged arc furnaces by tolerating additional carbon for the preferential reduction of iron and vanadium and successfully removing the titanium to the slag. In March 1963 the pilot plant tests paved the way to undertake an engineering study by Davy and United Engineering Company of Sheffield, for the full-scale construction of an iron, steel and vanadium plant.[1]

The iron making division currently consists of 13 Lurgi rotary kilns which supply direct reduced ore (DRI) to four closed-top submerged-arc Elkem furnaces and three Hatch designed Open slag bath furnaces. The ore processing starts at the iron plant in rotary kilns. The rotary kilns pre-reduce the ore in order to ultimately save energy when it eventually enters the electric arc furnaces. Combustion air is introduced to the kiln through air injector rings situated at the inlet end of the kiln, and air pipes distributed along the length of the kiln. These air pipes and injector rings are connected to air fans mounted on the outside kiln shell surface [1]. The kiln feed rate, pulverized coal and air injection are regulated in order to get a temperature profile inside the kiln close to a maximum of $1140^{o}C$. Figure 1 below shows a schematic illustration of the kiln and the air injectors. Pulverized coal is injected at the feed end and therefore results in a co-current firing mechanism.
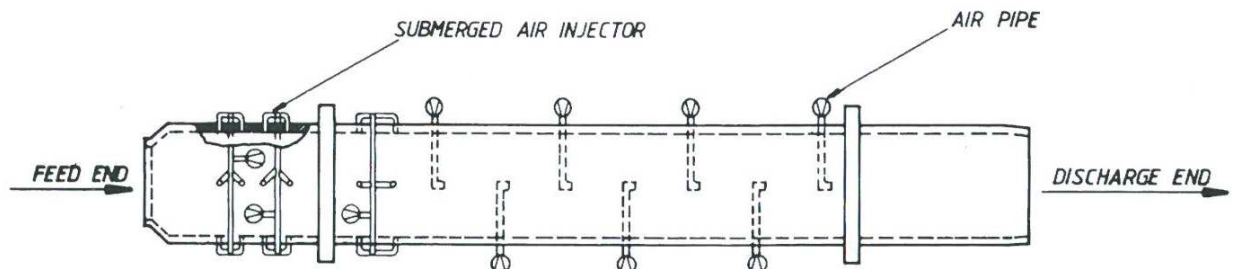
Figure 1*: Kiln air injector profile for the pre-reduction kilns at Highveld Steel and Vanadium.*

The kiln, as a pre-reducing unit, can typically be divided into two zones: a preheating zone and a reduction zone. In the preheating zone the feed mixture temperature is reached where reduction takes place and the devolatilization of coal occurs. In the last stage the iron oxide is reduced with char (devolatilized coal). Various studies have shown that the reduction kinetics of iron oxide by carbon is driven by temperature, carbon/iron oxide ratio, reducibility of the iron oxide and the reactivity of carbon. It is also shown that the size of the iron ore will affect the kinetics of reduction especially with dense particles. [2]

It is generally accepted that the reduction of iron oxide takes place in two steps, namely [2]

    I. Removal of oxygen from iron oxide by carbon monoxide

$$Fe_nO_m + nCO = nFe + mCO_2$$ ………………………………………………… 1

    II. Formation of reducing gas.

$$CO_2 + C = 2CO$$ ……………………………………………………… 2
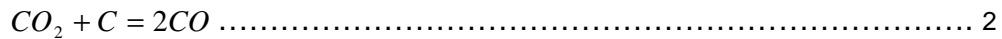
The heat source required by the kiln is provided by the burning of finely milled coal, called pulverized fuel (PF), and combustion of CO (as produced by the reduction reactions) above the bed of solids. These serve the purposes of heating the mixture to the desired reducing temperature and therefore igniting the coal in the bed for the gasification of coal according to the Boudouard reaction (equation 2). CO gas is the predominant reducing agent.

The energy saving that the kilns generate is summarized in two aspects:

- ***Pre-reduction*** – is done by gas and burning of PF which means less reduction by means of valuable electrical energy has to take place in the furnace. The magnetite ore is reduced to FeO and metallic iron.

- ***Sensible heat of furnace feed mixture*** – the hot kiln product has sensible heat that provides an additional energy credit for the electric furnace.

The economical decision to construct the kilns as a pre-reducing unit had good grounds, since the blast furnace technology, which is conventionally used for iron production, could not be utilized for the Highveld ore. The blast furnace provides very cost effective iron making with the most expensive aspect being the coke needed for its successful operation. The reason why Highveld could not utilize this option is mainly due to the high titanium content in the ore; the titanium tends to form titanium carbides and block the hearth and tuyères of the blast furnace. Although a successful blast furnace operation is run by Panzhihua Iron and Steel Corporation in China with TiO_2 content in their ore of 10.6 %,[3] it was not considered feasible in the 1960s to base the Highveld process on blast furnace technology with the Highveld ore TiO_2 content reaching 12.6%.

The smelting of hot pre-reduced titaniferous iron ore to produce pig iron and vanadium-containing slag for the production of vanadium products was started in the 1960s by both Highveld Steel and Vanadium, and New Zealand Steel (NZS). New Zealand Steel initially decided to use a mainly open bath foamy slag smelting mode while Highveld decided on submerged-arc furnaces. In 1980 NZS rebuilt their iron plant and changed their furnaces to rectangular 6-electrode-in-

line smelters in a partially open bath mode. They also use multi-hearth calciners ahead of the kilns.[4] This calcining step before the kilns allows the plant to focus on only iron oxide reduction in the kilns, and not devolatization and calcining of raw materials.

After approximately three decades the SAF process at Highveld has reached its maturity. It was decided in early 2000 that an investigation must be done to try to solve some of the problems experienced with the current SAF operation.[5]

Highveld aims to produce steel at low cost, while focusing also on recovering vanadium from the ore; hence producing two major sources of income for the company. At the Iron Plant the goal is to maximize the reduction of vanadium oxide into the liquid iron, and producing maximum tonnage of liquid metal. The vanadium in the liquid iron is then re-oxidized at the Steel Plant through the shaking-ladle process. The resulting oxidized vanadium slag is further processed to produce vanadium products used for ferrovanadium production and other vanadium chemicals. Maximization of vanadium recovery has become a large problem for the Iron Plant, and was one of the major drivers for the reassessment of the SAF.

The technical challenges faced by the SAF process are listed below.[6]

- Low vanadium yield – the average vanadium content in the iron of the submerged arc furnaces (SAF) for October 2008 was 1.00%, while that for the open slag bath furnaces (OSBF) was 1.16% for the same period.
- Low iron yield – mainly due to low iron temperature
- Low productivity – due to low power inputs. This is a result of erratic furnace carbon contents. The average metal production for the SAF was 284 t/day for July 2008, while for OSBF it was 344 t/day for the same period.
- Erratic product quality – higher sulphur values in the liquid iron. The average metal sulphur content of the SAF is 0.092% while for the OSBF is 0.037%.

When the drive to convert the SAFs at Highveld Steel to OSB furnaces started, it was thought that all these challenges would be overcome. It turned out that all of these challenges could indeed be overcome, but at a price. Much closer control over the entire process is required, necessitating better equipment and skilled operators.

The investigation and trial to optimize the smelting process at Highveld were completed in September 2003, at which point the approval was given to convert the first SAF to an open slag bath furnace (OSBF). Furnace 5 was commissioned as the first OSBF in December 2005. The Open Slag Bath technology is believed to be the future for the production of iron from the titaniferous magnetite. In the annual report for 2007 the CEO of Highveld (Walter Ballandino) confirmed that

the open slag bath furnaces will pave the way for increased steel and vanadium bearing slag production.[7] This is one of a few large capital investments planned for the company, which will help them reach their economic targets. This gave rise to the second and third open slag bath furnaces, commissioned in early 2007 and 2008. All three furnaces are currently operating at good production levels.

The ultimate aim of the work described in this dissertation is to capitalize on the additional opportunities that lie in the optimal operation of these OSB furnaces. This dissertation discusses some of the essential building blocks of an integrated furnace control system specifically formulated for the furnace configuration and Highveld's unique process challenges.

1.2 General differences between the submerged-arc and open slag bath furnaces at Highveld Steel.

In order to understand the detailed process control that will be discussed later, it is important to cover the basic operational drivers for the open slag bath furnace. The obvious starting point would be to highlight the major differences between the open slag bath furnace and the submerged-arc furnace.

1.2.1 Submerged-arc furnace

As the name suggests, the furnace electrodes are submerged in the direct reduced iron ore (DRI) and coke mixture. The Söderberg electrodes supply electrical power of approximately 24 MW to the furnace. The burden resistance transforms the electrical power into heat, which is used to melt the material. In a closer look at "dig-outs" done at a number of submerged-arc furnaces it is apparent that cool material is drawn in towards the reaction zone beneath the electrodes. [8] Due to the difference between slag and metal densities, the slag flows to the side of the electrode while the metal filters to the bottom. The temperature in the reaction zone is governed by the local mass and energy balance, including the rate at which fresh material is funneled in, and the liquidus temperature of the slag.[8] The lower the liquidus temperature of the slag, the easier smelting would take place. This will also be advantageous during tapping of slag since the slag viscosity is lower. Lower viscosity slags stimulate better separation between metal and slag droplets hence increasing yields.[9] The rate at which the molten material flows out of the reaction zone depends on the smelting energy requirements of the ore mixture. This aspect renders the SAF self-regulating. Material stays in the reaction zone, receiving heat from the arc, until it has reacted sufficiently to flow out of the reaction zone as liquid. This self-regulating capability of the SAF is both advantageous and limiting. [8] It makes the furnace flexible and easy to operate, but the control over the furnace is complex and ill defined. The typical zones inside the SAF are shown in figure 2.

The creation of a coke bed is very important, since it establishes a vital zone for the reduction reactions to take place.[8],[10] Lime and other high melting point materials are found mixed into the coke bed. The temperature drops steeply towards the upper part of the burden over a short distance from the electrode tip. These temperatures are estimated to be 1700°C at the electrode tip, dropping to 500°C at the most upper parts of the burden.[11] Solid state reduction takes place above the main reaction zone as the hot gas with CO content as high as 75% rises through the burden. In the operation of a submerged arc furnace the burden permeability is very important due to the high volumes of gas generated.[12] In some ferro-alloy production processes a second more reactive coke is used to sustain the reduction reactions. This coke is typically of a smaller particle size, which results in higher electrical resistance.

Heat distribution in submerged-arc furnaces plays an important role in product quality. The product quality can be maintained by controlling the fixed carbon

content in the burden and allowing for low enough furnace operating resistance. The operating resistance between the electrode tip and the furnace hearth is frequently too high due to poor electrode penetration. The attainable current density is strongly influenced by burden resistance, which depends on the furnace feed material. [10]
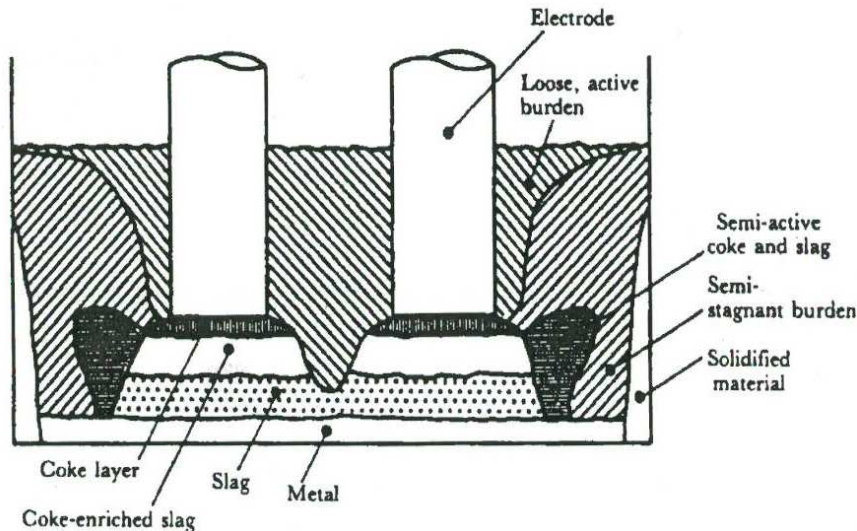
Figure 2: Cross section of a ferro-alloy furnace obtained from "dig-outs". [8]

The maintenance of the coke bed is of utmost importance to the consistent furnace operation, but the coke bed is disturbed by the tapping of metal and slag. This causes the coke bed to be disrupted or can even lead to complete drain outs. In order to compensate correctly for these drain outs, good electrode regulation and feed-forward carbon control are necessary. [8] Careful electrode management becomes important, since horizontal stresses are imposed on the self-baking electrodes. This can lead to electrode breaks, with a negative impact on productivity.

Other aspects that control the temperature in the reaction zone are the slag composition, electrode current density and the position of the electrode tip relative to the metal bath. Higher-basicity slags generally have higher melting points and will hence increase the temperature at the reaction zone. As the fresh material is added on the surface of the furnace burden, it is heated by both the hot ascending gases and the electrical current. Laboratory studies have shown that the resistivity of the half molten and completely molten material is several orders of magnitude less than that of cold material.[8] These tests have being done over several temperatures. For this reason 90 percent of the current, and therefore power generation, is limited to the region stretching between the electrode tip and the molten metal bath.[8] It follows that maintaining the correct electrode penetration is essential, since at a larger distance between the electrode tip and the metal bath the power density would be lower.[14] The active power input at each of the electrodes is given by equation 3:[14]

$$P_w = \frac{E_{r^2}}{R_f}$$ ……………………………………………………………………………….3

where: I   = electrode current
                 P_w = active furnace power
                 E_r = hearth voltage
                 R_f = hearth resistance.

The furnace can therefore be controlled by altering the transformer tap, which will influence the hearth voltage, and by changing the hearth resistance by changing the electrode position. Another important aspect is the reactance of the furnace, given by equation 4:[14]

$$X = 2\pi fL$$ …………………………………………………………………………..4

where   X   = reactive resistance per phase
                f   = current frequency
                L   = inductance.

Total furnace power can be described in two ways, namely constant voltage or constant resistance control. Constant voltage control is obtained by keeping the furnace transformer tap position constant and moving the electrodes up or down. By moving the electrodes, the arc resistance is changed which controls the electrode currents. This type of approach is described by equation 5 below.[13]

$$P_{tot} = 3 \times \kappa \times X \times I_{elec} \times \sqrt{(I_{max})^2 - (I_{elec})^2}$$ …………………………………………….5

The κ factor is known as the power factor, which depends on the inductive effects of the electrodes and conductors. I_{max} is given by V_{eb}/X where V_{eb} is the voltage between the metal bath and the electrode. For resistive heating, where no arcing occurs, $\kappa = 1$. Under normal submerged arc furnace conditions κ is typically 0.95.[13]

The constant resistance approach would be the equivalent of keeping the electrode tip position relative to the metal bath constant, and only using the furnace transformer tap position to control the power. This can be described by equation 6.[13]

$$P_{tot} = 3 \times (I_{elec})^2 \times R_{eb}$$ …………………………………………………………………….6

Figure 3 shows these characteristic curves for submerged-arc furnaces.
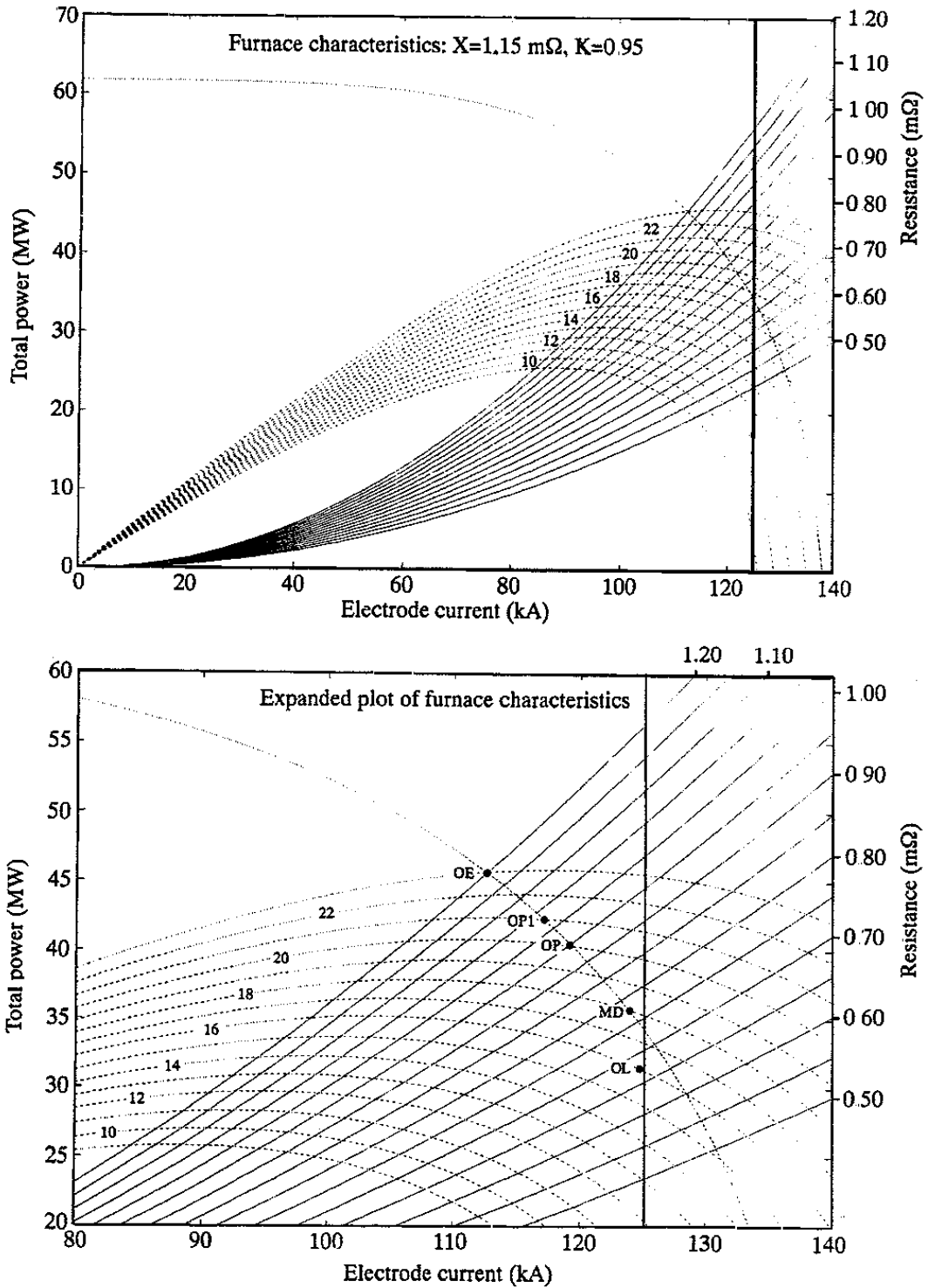
Figure 3: *Effect of varying resistance on electrode current and furnace power.*
Numbers 10 to 22 refer to different transformer taps.[13]

The degree of reduction in the reaction zone is driven by increased temperatures, if it is assumed that the furnace has sufficient carbon levels. The most important temperature controlling aspect is arguably the slag chemistry, since the higher the slag liquidus temperature the higher the reaction zone needs to be. Other aspects are the resistivity of the reaction zone (which is in turn controlled by reactive coke size distribution) and arcing. Arcing can be controlled by the electrode position relative to the coke – slag layer and the stability of the coke layer.

The resistivity of the furnace burden is mainly influenced by two factors in the Highveld operation:

- ***Kiln pre-reduction:*** The aim is to pre-reduce the ore mixture as much as possible in the kilns at Highveld. However, a high degree of metallization leads to a high conductivity of the material in the furnace. This high conductivity causes current to flow between the electrodes, and not through the coke bed and into the metal bath. The increased conductivity also has a negative effect on the furnace refractory, since the horizontal currents damage the refractories on the sidewall of the furnace.

- ***Carbon content of the furnace feed:*** The iron plant aims to produce an iron product which is suitable for steel production. In order to obtain the carbon specification and also to take part in the reduction reaction, carbon is added to the ore in the form of coal. The higher the carbon content of the furnace mixture material, the more conductive the material. In response to the high conductivity, the control system tends to lift the electrodes out of the burden to control the resistance; this causes operational limitations in terms of electrode lengths and stroke, as well as the passage of current between the electrodes and ineffective power utilization.

1.2.2 Open slag bath furnace

The main difference in the operation of the open slag bath furnace (in comparison with a submerged-arc furnace) is that the electrodes are arcing on top of the furnace contents and are not submerged in the burden. This arc condition is referred to as brush arc or open arc, which is obtained by controlling the position of the electrode tip. Figure 4 illustrates this concept.
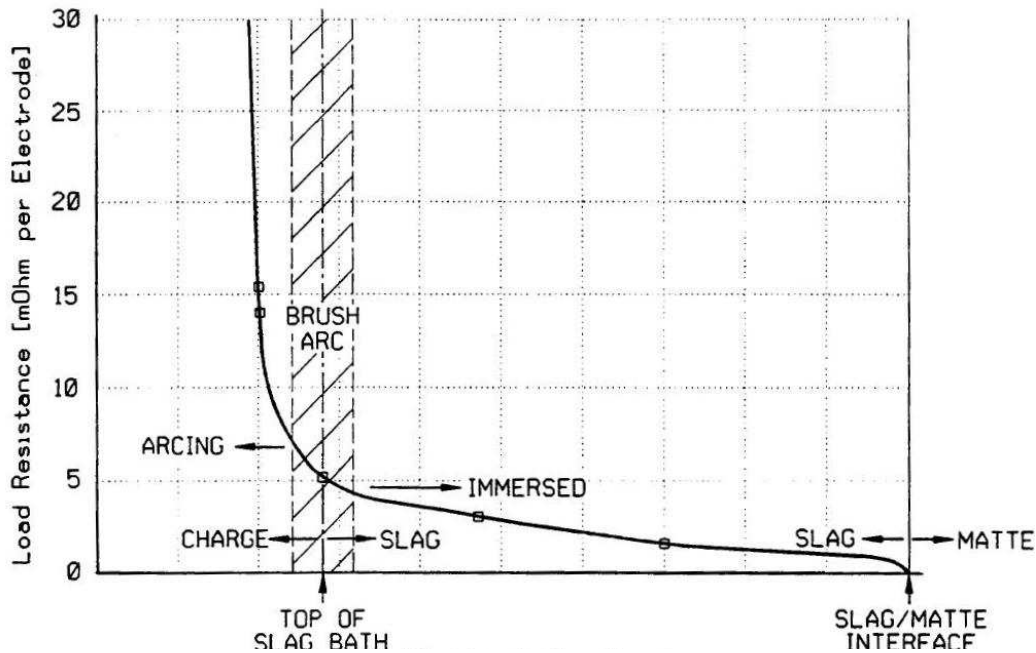
Figure 4: *The relationship between the operational resistance and the electrode tip position.*[14]

A brush arc leads to a number of advantages in the Highveld process: [6]

- The resistance to electrical current is not influenced by the properties of the mixture inside the furnace, but rather by the arc length.
- Melting of fines can be done, since burden permeability is not a limitation, unlike in the SAF.
- An open slag bath is created, where the superheated slag melts the furnace feed and therefore helps to separate the slag and metal to a larger extent.
- Due to the open slag bath, the product quality can directly be influenced by the feed mixture quality and its effect seen quickly. This provides an opportunity for fine chemistry control.
- Electrode penetration is no longer an issue, which means that constant power input is possible, uninfluenced by the burden properties.
- Improved furnace control is possible because more manipulated variables are available.
- The ability to control the slag composition inside the furnace by adding millscale.
- Enhancing the reduction kinetics, since most of the DRI is fed into the superheated slag right next to the electrodes.

The operation of an open arc also holds a few risks. The first is that the open bath area will result in higher heat losses through the roof of the furnace. This will decrease the energy efficiency and could lead to high roof refractory wear rates.

However, given the higher metal production rate in the OBSF, the energy consumption per ton could in fact be decreased compared to the SAF, if similar or better furnace availability is maintained. From practical experience, the roof cooling system which was part of the OSBF has successfully eliminated excessive refractory wear. An obvious difference between the SAF and the OSBF is the importance of the feed rate control. The SAF is a self-regulating furnace, with a choke feed. In contrast, the OSBF is extremely sensitive to feed rate and to the distribution of DRI around the furnace perimeter. [6] This is discussed in more detail in the next chapter.

The principle of the OSBF is illustrated in figure 5. It can be seen that the feed material enters the furnace through feed pipes, which pass through the roof of the furnace. The feed piles that are created are consumed from the inside of the furnace as well as from the bottoms of the piles. The advantage of having the feed piles covering the sidewall of the furnace is threefold. Firstly it protects the sidewall refractory from the intense heat of the open arc. Secondly it creates an open bath, which allows the electrodes to arc on the slag layer and lastly it provides additional material for cooling. The combination of larger power inputs and arcing on the more refractory slag create larger superheats in the iron, compared with the SAF.

The distinct slag and iron layers allow the use of two tap holes on different levels. The slag tap hole is 60 centimeters higher than the iron tap hole, which makes it possible to know what will be tapped at every given moment. The higher reaction temperatures result in higher carbon contents (by dissolution) in the iron, lowering the iron melting point. This tends to increase the iron yield, since launder and ladle sculling are minimized. The increased reaction kinetics and high slag temperature should also give higher vanadium recovery, which is a direct economical driver for the OSBF operation. The OSBF also achieves increased sulphur removal because higher slag basicity is used, increasing the free oxygen anion concentration in the slag and so favoring desulphurization according to reaction 5.

$$[S] + (O^{2-}) = (S^{2-}) + [O]$$ ………………………………………………….. 5

The OSBF at Highveld is operated with a constant voltage setting, which means that the transformer tap position is kept constant as far as possible while the current is controlled by moving the electrodes up and down.
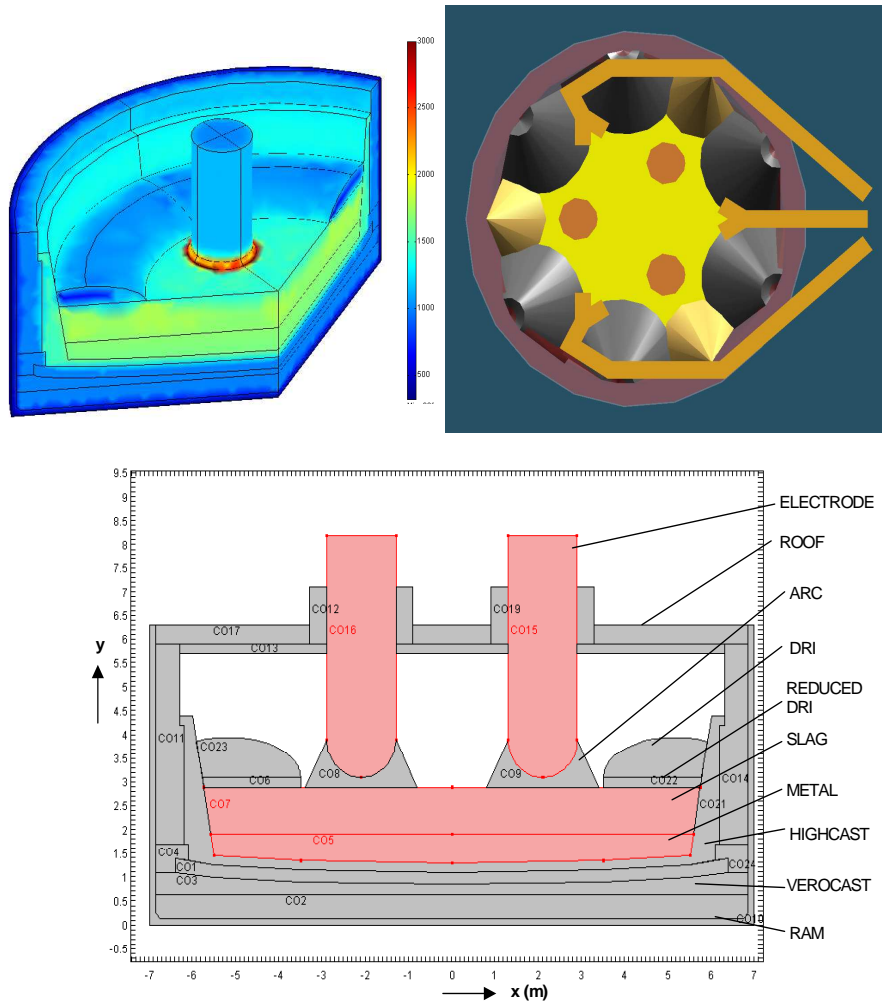
Figure 5: *General configuration of the open slag bath furnace.[5]*

2. Detailed process description of the open slag bath furnace

A low-cost source of iron ore is received form Mapochs, Highveld's mine facility situated north of the village of Roossenekal in Mpumalanga. The typical chemical composition of the ore is shown in table 1 below.

Table 1: Typical Highveld iron ore composition[15]

Fe(t)	FeO	Fe_2O_3	SiO_2	Al_2O_3	MgO	CaO	MnO	V_2O_5	Cr_2O_3	TiO_2
54.80%	16.50%	60.00%	2.00%	4.80%	1.60%	0.10%	0.30%	1.65%	0.40%	12.70%

The ore is processed in a two-stage operation. The first stage is the pre-reduction of the ore in rotary kilns. The kilns are 60 meter long refractory lined vessels, which produce approximately 36 t/hr DRI. The kiln feed consists of 63% ore, 28% coal and 9% dolomite. Coal is added in order to provide the reactions with sufficient reductant and also to yield a specified amount of carbon in the final iron product. Dolomite is added to establish a required basicity. Basicity is a very important aspect in the furnace, since it controls the slag viscosity, reduction state and temperature. The slag volume of the OSBF was reduced compared to the SAF, by decreasing the amount of silica in the feed mixture. This allows for a higher basicity in the OSB furnaces compared to the SAFs, which aids in sulphur removal. The lower basicity is necessary in the submerged arc furnace due to the lower operating temperatures and therefore reduced slag liquidus temperatures. Due to the additional heat loss of the OSB furnaces created by its open bath, lowering the silica content reduces the slag volume and helps to conserve energy.

Currently the kilns obtain an average of 45% pre-reduction. The DRI feed material is transferred to the hot-charge area, which is situated two levels above the furnace floor. The DRI is gravity fed through feed pipes into the furnace, in order to establish steady state feed piles. The concept of constant and correct feed rate is the single most important variable in the stability of furnace operation, as will become evident as the discussion develops.

The reduction of iron oxide is the main reaction that takes place in the furnace, and the overall reaction is shown below.

$$FeO + C = Fe + CO \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

Small amounts of iron oxide remain unreduced and report to the slag. The control of the FeO in the slag is very important since the slag oxygen potential determines the residual element reduction rate.[15]

The residual elements that are also sensitive to the reduction conditions are listed below.[15]

$$TiO_2 + 2C = Ti + 2CO \quad ....………7a$$
$$TiO_2 + \tfrac{1}{2}C = TiO_{1.5} + \tfrac{1}{2}CO... 7b$$
$$SiO_2 + 2C = Si + 2CO \quad .... 8$$
$$V_2O_3 + 3C = 2V + 3CO \quad .... 9$$
$$MnO + C = Mn + CO \quad .... 10$$
$$Cr_2O_3 + 3C = 2Cr + 3CO \quad .... 11$$
$$P_2O_5 + 5C = 2P + 5CO \quad .... 12$$

The reduction of these compounds depends on temperature and oxygen activity, leading to different degrees of partitioning between the iron and the slag. The reduction of TiO_2 to Ti metal is used as a chemistry control indicator at the plant.

2.1 Feed mixture characteristics and typical energy consumption [15]

Typical values as calculated by Geoff Randall, who acted as consultant to Highveld Steel, are given in this section:

A typical kiln feed mixture which yields the correct slag basicity and iron chemistry is listed below.

- *1000 kg iron ore*
- *440 kg wet metallurgical coal (approximately 3% moisture)*
- *220 kg dolomite*
- *15 kg silica*

A typical furnace feed mixture is as follows.

- *3.4% char*
- *2.5% free ash*
- *84% reduced ore and flux*
- *10.1% carbon*

From 1000 kg iron ore, 548 kg of iron is produced at a temperature of 1350 ^{o}C and 448 kg of slag is produced at a temperature of 1440°C. Additionally gas is produced at a rate of 345 Nm^3/t iron. The typical slag and iron analysis are shown in table 2 below.

Table 2*: typical iron and slag analysis of the OSBF*

Ti	Fe	Si	Mn	V	Cr	C			
0.20%	94.50%	0.20%	0.20%	1.29%	0.34%	3.20%			
TiO_2	TiO_3	FeO	SiO_2	Al_2O_3	MgO	CaO	MnO	V_2O_5	Cr_2O_3
35.60%	10.10%	1.00%	16.20%	18.00%	14.10%	14.70%	0.40%	0.90%	0.20%

Carbon is extensively used in the process to reduce the different elements but also to establish a suitable amount of carbon in the iron. The carbon usage is listed below.

- *Reduction of FeO and Fe$_2$O$_3$*   *77.8%*
- *Carbon in iron*   *14.5%*
- *Reduction of V$_2$O$_5$ to V*   *3.3%*
- *Reduction of TiO$_2$ to Ti$_2$O$_3$ and Ti*   *2.9%*
- *Reduction of other oxides*   *1.5%*

The energy usage of the process is estimated to be as follows:

- *Reduction of iron oxides*   *41.7%*
- *Sensible heat of iron*   *22.5%*
- *Sensible heat of slag*   *17.9%*
- *Sensible heat of waste gas*   *11.1%*
- *Other reactions*   *6.8%*

In order to support these reactions and energy demands the process obtains its energy from two sources namely:

- *Energy from electric power*   *74.2%*
- *Energy from pre-heated and pre-reduced feed*   *25.8%*

An important aspect to the energy balance is the losses of energy associated with the process. The approximated heat losses from the different sections of the furnace are listed below.

- *Hearth*   *415 kW*
- *Lower side wall*   *264 kW*
- *Upper side wall*   *1323 kW*
- *Furnace roof*   *4924 kW*
- *Electrical losses (approx 2%)*   *141 kW*
                                          7067 kW

2.2 Heating cycle of the Open Slag Bath furnace

In a recent document that was written by Geoff Randall,[15] the heating cycle of the furnace was described with a wax model. This description provided a very simple but informative illustration of the conditions inside the furnace. A wax model concept was also used in work done by Robertson and Kang[16] to design cooling panels for the wall of slag cleaning furnaces. They found that wax is a good medium to simulate the heat transfer principals of slag since it also has a high Prandtl number. It cannot be used to simulate the conditions near the arc, but at the furnace wall simulations can be conducted.[16]

The wax-melting analogy can be summarized as follows. Imagine a cylindrical steel container, filled with wax, with a heating element inserted in the middle of the container, as illustrated in figure 6a. When no power is supplied to the element the wax will be solid throughout the container. As soon as the element is

switched on and is set to supply a low power to the surrounding wax a thermal gradient starts to develop. The wax that touches the element has nearly the same temperature as the heating element itself. As long as the rate of heat supplied by the element is such that the interfacial temperature is lower than the melting point of the wax, the wax stays solid. If the rate of heat supply is increased such that the interfacial temperature increases to the melting point of the wax, the wax starts to melt. Increased power input would cause the melted wax zone to advance towards the outside of the container. The temperature profile then changes such that the highest temperature will be next to the heating element, and the average temperature of the liquid wax will be higher than its melting point (superheat). The wax will melt up to the point where the temperature of the wax is equal to its melting point. This concept is illustrated in figure 6b.[15]
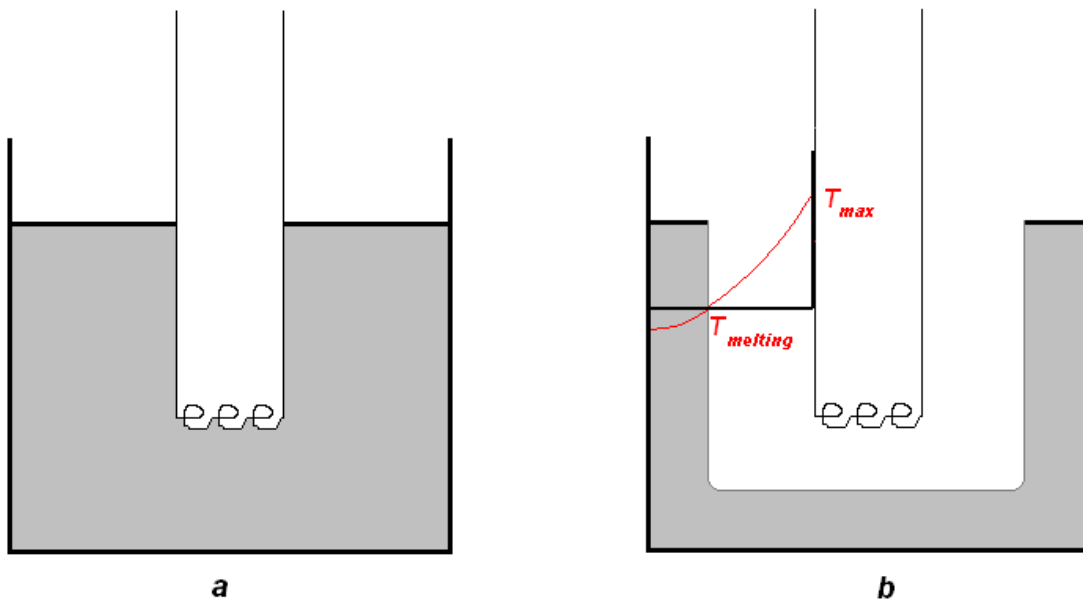
Figure 6: *Schematic illustration of the wax model concept to explain the thermal states of an electrical furnace. (a) When the heating element is supplying power at a rate such that the interfacial temperature is less than the melting point of the wax. (b) When the element is supplying power such that the interfacial temperature is above the melting point of the wax.*

The liquid area around the heating element is now referred to as the open bath. This illustrates, in very simple terms, the power input and bath size relationship. The matter becomes more complicated when fresh material is added to the liquid bath. This is illustrated in figure 7.
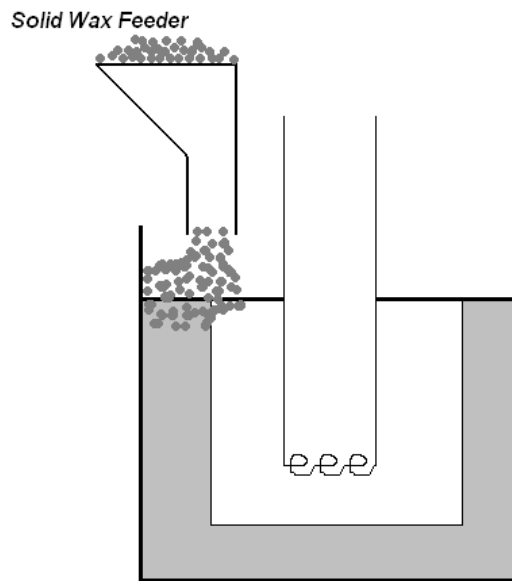
Figure 7: *The situation where the liquid wax bath is fed with solid wax particles.*

A continuous feed of unmelted wax, changes the energy balance completely. As the wax enters the liquid bath, power is used to melt the new wax, and less power is available to maintain the liquid bath. If the power input from the element were to stay constant, the result would be a decrease in the steady-state size of the liquid bath. If the feed rate of the new wax were increased more power would be used to melt the wax, which would decrease the size of the open liquid bath. This effect can be severe and a so-called "overcharged condition" can develop. Conversely, an undercharged condition might develop if too little wax is supplied. The latter is an extremely dangerous situation, since the furnace refractories can be damaged, ultimately leading to a melt-through.

The following energy balance holds in this simple model furnace:

Power input = (Heat losses to environment)
+ (Theoretical energy x Mixture feed rate).

Where: **Theoretical energy** = energy required to melt the feed mixture (kJ/t)

If it is assumed that the energy heat losses to the environment and the theoretical energy needed are constants, it is clear that the energy balance of the furnace is controlled by only two variables, namely:

- **Feed rate of the kiln product into the furnace**
- **Power input (MW)**

2.3 Effect of downtime on the furnace energy balance

There are many events that can cause the furnace to be switched off, resulting in a decrease or loss of power input, and hence an upset in the energy balance. The following are typical reasons for furnace downtime:

- ▪ **Furnace trips**: *all the furnace support systems are connected to the SCADA (Supervisory Control And Data Acquisition) system which monitors their performance. One example is the cooling water of the furnace roof panels. If the water outlet temperature reaches a particular level the SCADA system will trigger a furnace trip. There are many such examples which make the effect of furnace trips significant.*

- ▪ **Feed pile measurements**: *once every 12 hours the furnace must be switched off to measure the height of the feed piles inside the furnace. This information is used to determine the charging condition of the furnace.*

- ▪ **Power reduction due to ESKOM problems**: *with the current power shortages that are experienced in South Africa, it happens from time to time that the power supply to the furnaces is reduced to levels well below the normal operating condition.*

- ▪ **General maintenance**: *when general maintenance must be done on the furnace, the power is switched off, especially when the work is done on the furnace roof section or on the electrodes.*

- ▪ **Feed mixture shortages**: *any problem at the kilns (which supply the furnaces with feed) will result in feed mixture shortages. This shortage in DRI will lead to reduced or no power input to the furnace.*

- ▪ **Unblocking of screw feeders and charging shafts**: *due to the current design it happens frequently that large ore pieces or foreign objects block these chutes. The furnace then has to be switched out in order to unblock the particular section.*

- ▪ **Electrodes limiting**: *when the furnace inventory becomes high, the electrodes reach their upper limit of movement. The power input is then decreased (for safety reasons) by decreasing the transformer tap.*

The above reasons for furnace outages can accumulate in substantial losses of energy from the system. Even when producing no iron, the furnace loses heat at a rate of approximately 7 MW. Also, if the feed rate of the mixture is not regulated carefully, the energy balance of the furnace cannot be controlled.

2.4 The effect of the energy balance on the furnace chemistry

There are three aspects that will govern the furnace chemistry, namely:

- *Furnace feed material chemistry*
- *Effective temperature in the furnace*
- *Secondary melting effects.*

2.4.1 Furnace feed material chemistry

The furnace was originally designed with a relatively large permanent metal inventory below the iron taphole, to act as a buffer. Such a buffer should decrease fluctuations in metal composition. The presence of a large metal inventory makes is difficult to detect links between feed mixture composition and the product tapping composition, due to a long retention time in the process.

2.4.2 Secondary melting affects [15]

The effect that the internal arrangement of new ore and melted material has on the overall chemistry must also be considered. The furnace can be in three basic conditions, namely:

- ***Overcharged***: *when there is a shortfall of energy to balance the accumulated material in the furnace.*
- ***Undercharged***: *when the feed rate is too low for the power input.*
- ***Good (balanced) condition***: *the power and feed rate are in balance, thus the power is just sufficient to consume the feed material.*

As new un-melted wax is added to the wax model, more energy is required to melt the wax. Similarly if the feed rate increases too much, the furnace can go into an overcharged condition. With a constant power input and increased feed rate, the available energy to maintain the melted wax will effectively decrease. Keeping this in mind the two different melting modes must first be described in order to continue with the discussion.

Figure 8 below shows a schematic vertical section through the furnace, showing the feed pile profile. *Mode A* melting is when the bath is open and the fresh feed is consumed readily from the inside of the furnace to the outside (horizontal melting). *Mode B* melting is when the bath is covered, so that fresh material is simply piled on top of the current material. Melting therefore occurs mainly from the bottom and therefore termed vertical melting. Mode A melting is expected to be much faster, since the material lies in the hottest part of the furnace. With Mode B a slower selective melting process occurs.
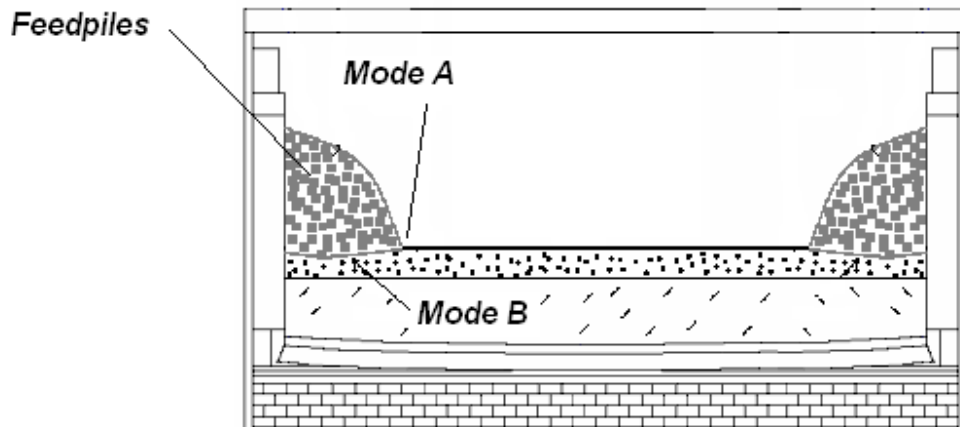
Figure 8*: The two different melting modes inside the furnace.*

When the furnace is in an overcharged condition the feed piles grow towards the electrodes, shrinking the bath. When the furnace is completely "closed" (mode B melting occurs predominately) the slag and metal chemistry will not respond as rapidly to changes in the feed material since the furnace burden shields the liquid bath from the fresh feed mixture.

In the fully-closed and overcharged condition, the reaction temperature in the furnace is expected to decrease, and the extent of reduction in the slag is also expected to decrease. The FeO content in the slag gives an indication of the effective oxygen potential in the system. In the fully-closed condition the equilibrium is expected to shift to a more oxidizing condition and less Ti and V will be reduced. Given the too-low power input, selective melting of the low melting point components is expected. As overcharging continues, unreacted carbon would accumulate in the banks. The feed banks will crust and shield the newly charged material from the furnace.

Due to the shift in the equilibrium towards more oxidizing conditions, more FeO will be present in the slag. FeO fluxes the slag which means that it reduces its melting point. The reduction in the melting point will effectively increase the slag superheat, which can be expected to lead to the opening up of the slag bath in order for mode A melting to dominate again. This continual change in the melting modes will influence the chemistry of the tapped iron, since it is believed that different chemistry regions exist inside the feed banks and lead to different chemistries to be exposed to the slag bath. Figure 9 below illustrates these regions, and these regions are discussed in more detail below.
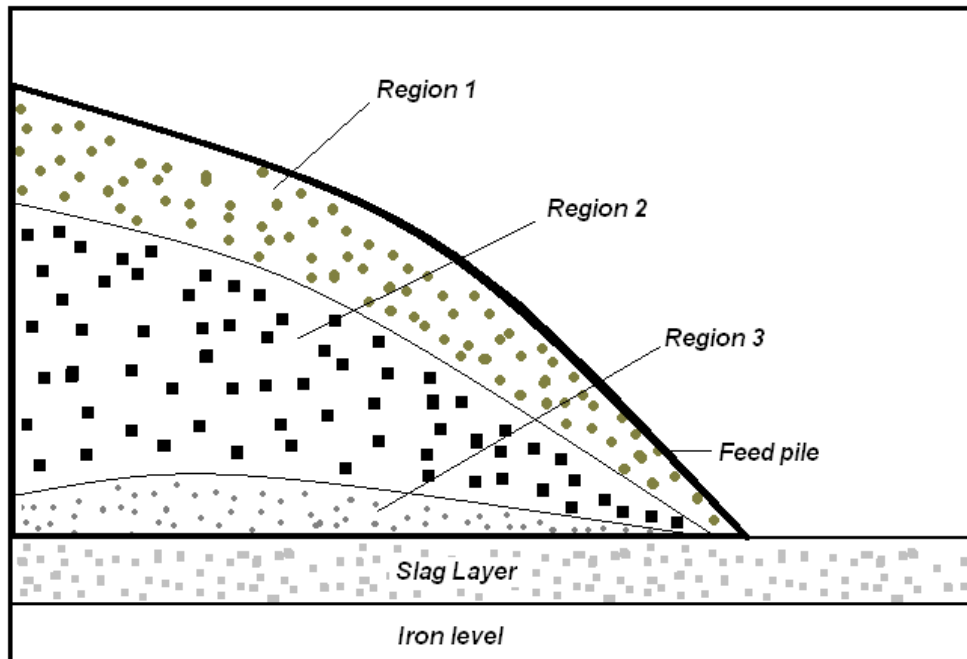
Figure 9: *The presumed chemistry regions inside the furnace feed pile.*

The regions that are believed to be present inside the feed pile, as illustrated in figure 9, have the following features:

- ■ *Region 1* – this layer of material is the same as that of the kiln product. The fresh material will trickle down towards the electrodes and end up in the open slag bath, only if the bath is open and not overcharged.
- ■ *Region 2* – this region is known as the refractory region and contains the high melting point components and is believed to be high in carbon and a high basicity.
- ■ *Region 3* – this region is the low melting point component region, usually deprived of carbon.

Due to these expected different chemistry regions inside the feed pile it becomes very important to understand the different melting modes and how they influence the furnace chemistry and the redox conditions. It again comes down to controlling the power/feed rate ratio in order to obtain a constant open slag bath.

This feed pile configuration inside the furnace can be used to our advantage by altering the slag superheat. The slag temperature controls to a large extent the vanadium recovery and also the slag viscosity, which impacts on the slag tapping. Figure 10 below explains this concept better.
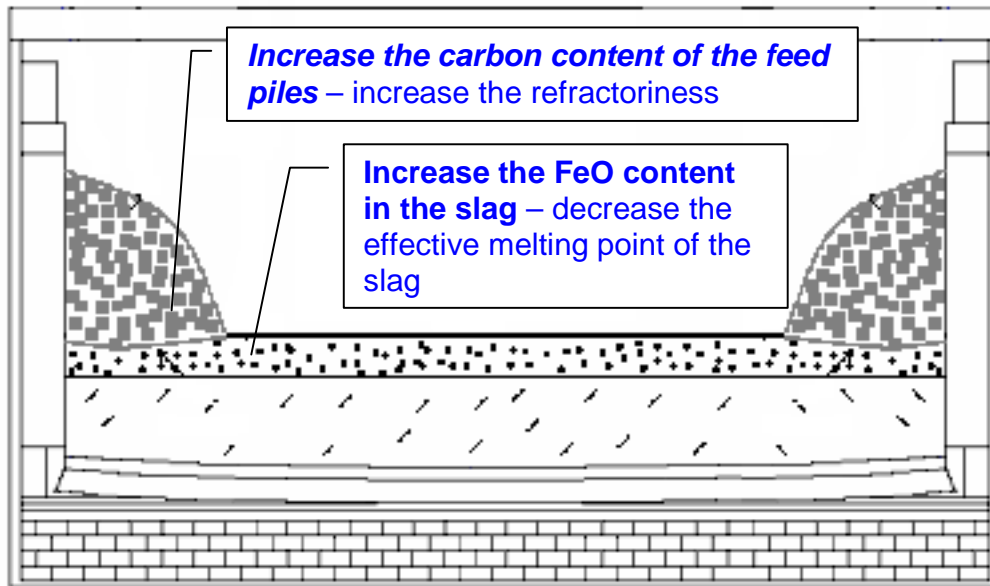
Figure 10: Illustration of how the ability of the slag to melt the banks can be controlled by the feed chemistry.

A theory does exist that by operating the kilns on excess carbon, the feed piles will become more difficult to melt due to their increased refractoriness caused by the excess carbon. By creating this increased slag bath temperature caused by the resistance in the melting of the feed banks, the superheat of the slag can be increased. This would lead to an increase in vanadium recovery. On the other hand the liquid slag bath can be fluxed by adding FeO in the form of millscale [15]. The detail behind this theory is not fully understood though.

2.5 Importance of furnace slag control

It is of utmost importance to understand the chemistry of the furnace, considering both iron and slag. Although the slag is not of direct economical importance to the iron making division, it certainly effects the furnace operation, vanadium recovery as well as the iron yield and contributes to costs.

Should it not be possible to tap slag at regular intervals it would severely affect the furnace operation, through increased inventory inside the furnace and electrode stability difficulties. High slag inventories also increases heat losses through the furnace roof, since a larger surface area of open slag bath increases radiation towards the roof. If slag inventory becomes too high, it could lead to furnace downtime since no additional feed mixture is allowed to be charged into the furnace if the electrodes reach their upper limit.

The iron yield is influenced by the slag condition, since high viscosity slags tend to entrap iron droplets and therefore reduce the iron separation. If a slag of higher superheat could be established it would lead to better separation between

slag and metal through lower viscosity. Analysis of plant samples has shown that slags made by the SAF contain approximately 5% recoverable metallic particles, while slags originated from the OSB furnaces contain less than 3%.

The main focus of this section is to try to highlight the important aspects that control the slag condition and also to map out an area of best slag practice considering the various operational and chemical challenges mentioned above. This section will summarize work that was done by various authors regarding this topic.

2.5.1 Solidification behavior

Different studies[17,18,19, 20] indicate that the expected primary solid phases are magnesium spinel or perovskite ($CaTiO_3$). Background research for the original Highveld project [21] showed the primary phase to shift from perovksite at high CaO levels, to pseudobrookite (M_3O_5) at high MgO levels (Figure 11). In line with the data of Figure 11, Ratchev and Belton [19] also concluded that these slag systems have a large solidification range.
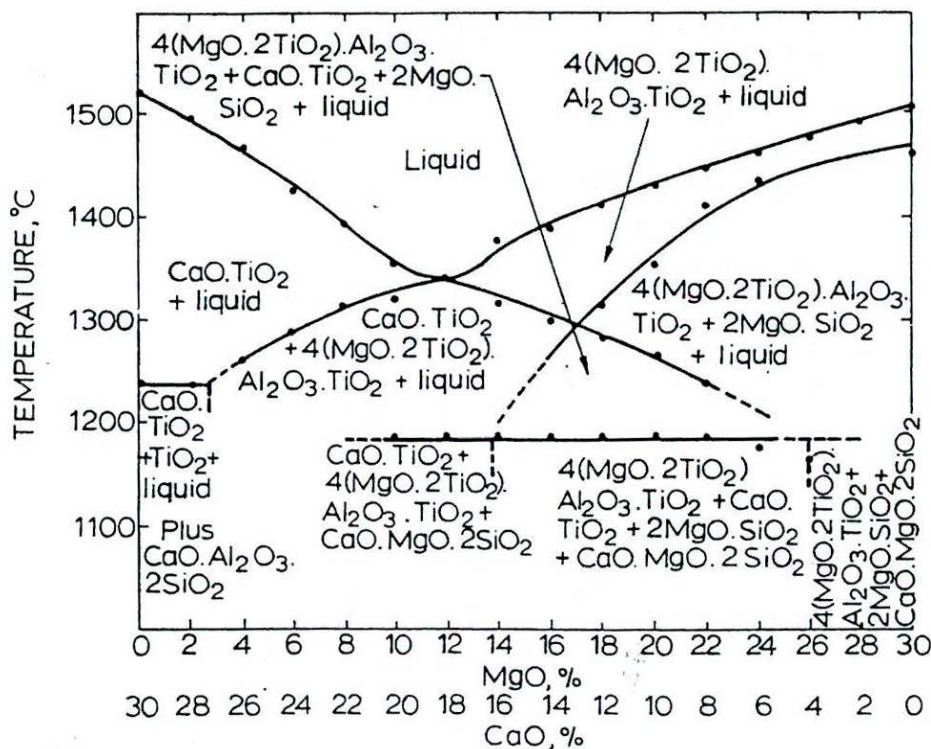
Figure 11: Effect of changed proportions of MgO and CaO on the liquidus temperature of Highveld Steel ironmaking slag.

In the study by Nell [20] it was concluded that when the primary phase is perovskite, the liquidus temperature is controlled by CaO addition, irrespective of

the MgO/SiO_2 ratio. He showed a liquidus temperature increase from 1350^oC to 1600^oC with a CaO variation of 14% - 20%. For spinel as primary phase, the liquidus temperature was controlled by the SiO_2 content, and showed a decrease from 1500^oC – 1350^oC with an 18% - 24% variation in SiO_2. Jochens et al. [21] also showed a liquidus temperature decrease with the decrease in CaO. Figure 11 shows that the slag liquidus temperature changed from 1520^oC at 30% CaO and 0% MgO to 1505^oC at 0% CaO and 30% MgO. It can also be seen from Figure 11 that the liquidus passes through a minimum of 1340^oC at 18% CaO and 12% MgO.

2.5.2 Total titanium content in the slag reported as TiO_2 and the state of reduction of the titanium

All the studies that were investigated for this section concluded that the trivalent titanium component or the Ti^{3+}/Ti^{4+} ratio impacts strongly on the liquidus temperature of the slag. Ratchev and Belton[19] showed that a 21.6% reduction of titanium from Ti^{4+} to Ti^{3+} (for New Zealand Steel slags) resulted in an increase in the liquidus temperature by 140^oC.

The Ti^{3+}/Ti^{4+} ratio increased weakly with the TiO_2 content in the slag (figure 12), but depended strongly on basicity and oxygen activity.
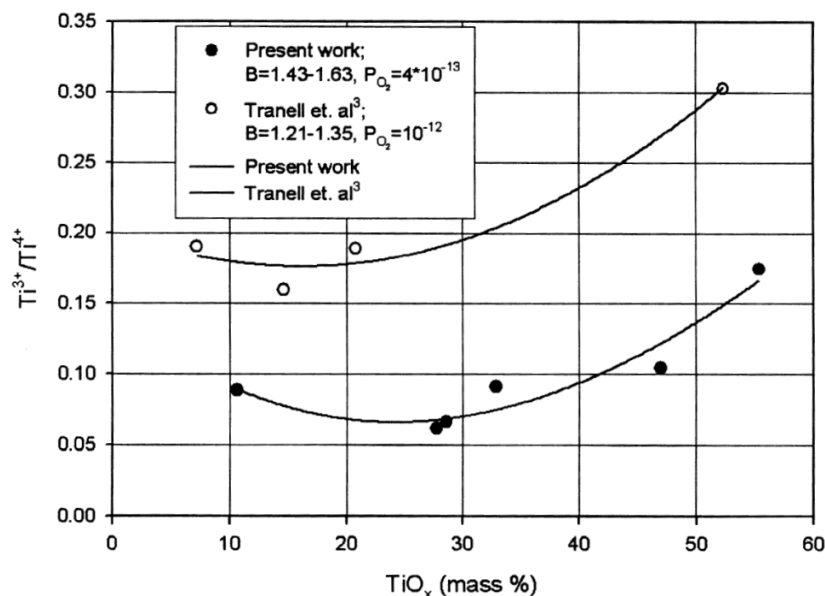
Figure 12: The effect of TiO_2 content and oxygen activity on the oxdiation state of titanium in $CaO-SiO_2-TiO_2$ slags.[19]

2.5.3 Slag basicity

The study by Ratchev and Belton [19] showed that small variations in slag basicity resulted in considerable variation in the liquidus temperatures of the slag (Figure 13). This is in line with the findings of Holmes *et al.*[22]. This latter was a three-part study on the liquidus temperatures of titaniferous slags, where a lab scale electric arc furnace was used to semi-continuously produce pig iron and slag. After this extensive study it was concluded that basicity is the most important variable regarding the liquidus temperature and the reduction state. Nell [20] similarly found that it is possible to modify the liquidus temperature and the Ti^{3+}/Ti^{4+} by changing the basicity. The interrelationship between basicity, and titanium reduction state and liquidus temperature was also illustrated by Xie *et al.*[23] They concluded that the liquidus temperature of high-basicity slags ($CaO/SiO_2=1.4$) *decreased* with increased reduction (higher Ti^{3+}/Ti^{4+} ratios), whereas low-basicity slags ($CaO/SiO_2 < 0.8$) had increased liquidus temperatures with increased reduction.
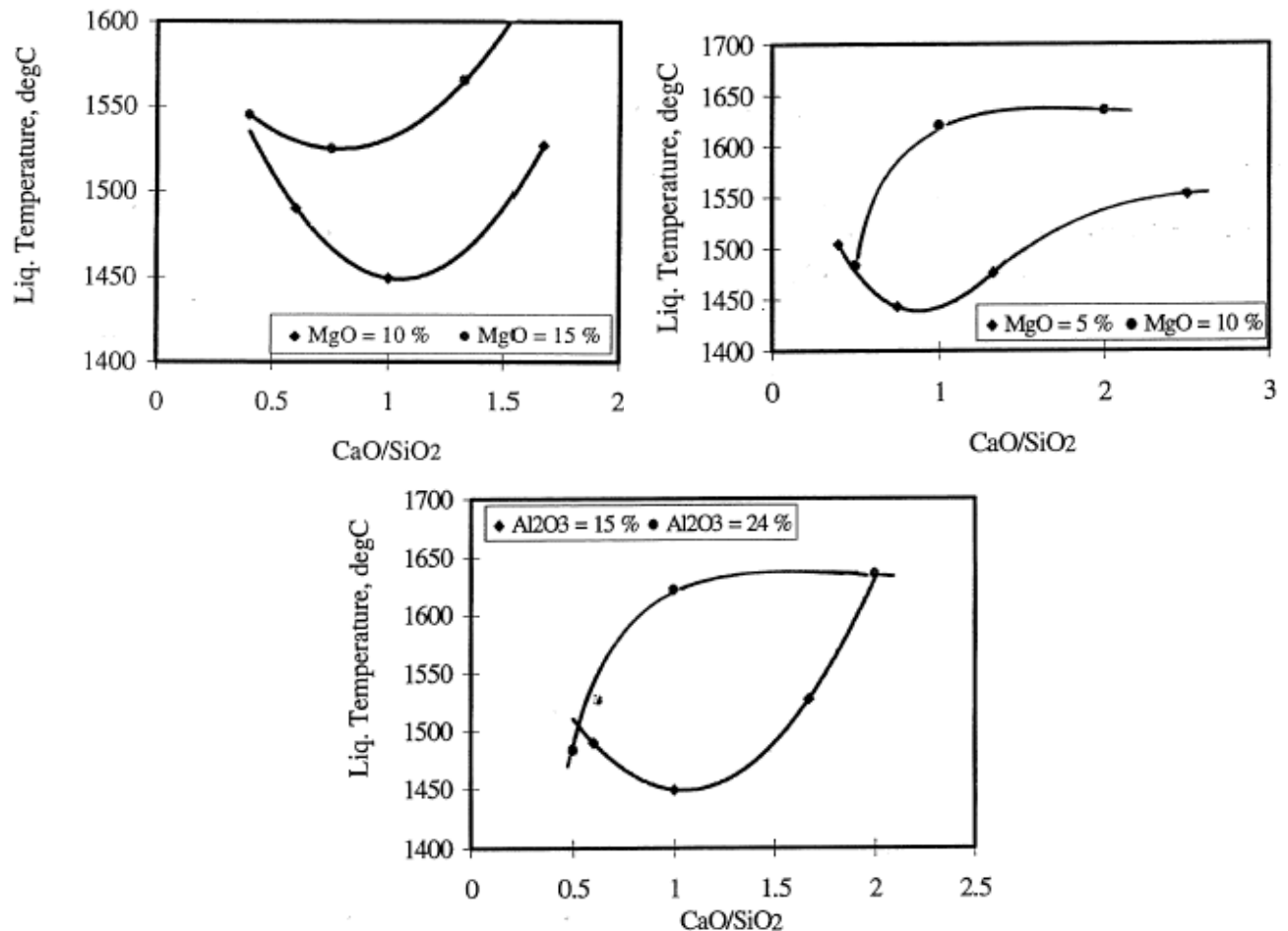
Figure 13: *Typical slag liquidus temperatures for different basicities (New Zealand Steel slags)*[21]

Based on thermodynamic modelling of Highveld furnace slags Nell [20] concluded that it is possible to modify the liquidus temperature and the Ti^{3+}/Ti^{4+} ratio by changing the basicity ratio. In his work it was shown that lower basicity resulted in lower liquidus temperatures and less reduction. This however might also result in less vanadium recovery to the iron.

2.5.4 Slag viscosity

Two independent studies by Xie *et al.*[23] and Zhang and Jahanshahi [24] concluded that the viscosity of these slags is a strong function of temperature and TiO_2 content; increasing TiO_x decreased the viscosity of the slag, in line with the earlier survey of Sommerville and Bell [25]. Highly reducing conditions, leading to the formation of solid TiC or TiO-TiC solid solutions, cause the apparent viscosity to increase.

2.5.5 Other slag components

Ratchev and Belton [19] showed that FeO in the slag decreased the liquidus temperature by approximately $70^{o}C$ at FeO levels of 8%, but FeO did not have a significant effect at levels below 4.5%; MnO at levels below 5.3% also did not have any influence on the liquidus temperature.

2.6 Current furnace chemistry control

Currently the furnace is chemically controlled by introducing correction material in the form of millscale. The millscale is predominantly iron oxide. The millscale is introduced in the centre of the furnace between the three electrodes. This correction material is used to alter the oxygen potential in the slag, so correcting extreme reducing conditions. If conditions are too strongly reducing, TiO_2 is reduced to Ti_2O_3 and to Ti in the metal, which could impact on furnace productivity if not controlled carefully.

The only two inputs available to control the furnace metal chemistry directly are the carbon content of the kiln feed and the correction material addition to the furnace. The slag chemistry is controlled by adjusting the dolomite and silica settings. The aim purpose of the slag chemistry control is to obtain a correct basicity and to dilute the TiO_2 content sufficiently. These variables are used to maintain the delicate balance in the furnace. The difficulty in this control is the effective quantification of the variables and their effect on the process. Without a quantitative guideline for the variation of these variables, no stability is possible, since each operator change them as they feel comfortable with.

2.7 Furnace corrective action matrix [15]

In the course of this project it rapidly became clear that many aspects influence chemistry control of the open slag bath furnaces. Bath condition, carbon content, residual element reduction (Ti and V concentration), FeO content in the slag[1] and melting modes are all important aspects which should potentially be taken into consideration regarding furnace chemistry control. The question now becomes when and by how much these variables should be changed to control the furnace state within reasonable limits. Table 3 below shows different scenarios regarding these variables. The proposed corrective action will also be discussed, but the quantum of change will only be discussed later in this dissertation. In table 3 below the following terms are used:

"Chemistry satisfactory": this refers to a carbon content of 3.5%, vanadium of 1.2% and titanium content of 0.18%
"Charging condition": describes whether the furnace is full of mixture (overcharged) or deprived of mixture (undercharged).

The latest metal tap analysis is used to determine the furnace chemistry condition; this is available roughly every 4 - 6 hours. The furnace charging condition is determined every 8 hours by doing a physical furnace inspection. The foreman decides which charging condition strategy will be followed and for how long. The titanium content of the iron is used as a redox indication, rather than using FeO. The reason for this choice is that the slag at Highveld is analysed using X-ray fluorescence (XRF), which cannot distinguish between FeO and metallic iron. On a trial basis, a few slag samples were analysed for their FeO and metallic Fe content. These results are shown later. Correction material in the form of FeO is added in some instances to change the oxidation state of the slag. This effectively mops up additional carbon and therefore decreases the tendency of the titanium oxide to be reduced.

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[1] FeO is mentioned here although the Ti content of the metal is the practically used indicator of the extent of reduction on the plant. This is due to the difficulty of analyzing for FeO (separately from entrained metallic iron) at the Highveld laboratory, as discussed later.

Table 3: Corrective action matrix for the optimal furnace chemistry control

Chemistry / Power	High Ti content Excess Carbon	Chemistry Satisfactory	Low Ti content Deficient Carbon
Excess power, Expanding bath	**6**. See text	**4**. Increase Feed/Power ratio	**7**. See text
Satisfactory bath condition	**3**. Change mixture, Increase iron ore Re-calculate power	**1**. No Change	**2**. Change mixture Decrease iron ore Re-calculate power
Deficient power, Shrinking bath	**8**. See text	**5**. Decrease Feed/Power ratio	**9**. See text

1. The furnace chemistry and charging condition are satisfactory, which means that the furnace operators do not need to make any changes.

2. In this scenario the charging condition seems to be correct. The low titanium content in the metal can be due to a high rate of correction material addition or low carbon content in the kiln feed. The correct cause of action would be to reduce the correction material addition. If this is already zero the carbon setting on the kilns can be increased.

3. This scenario also shows a good charging condition, which means that the energy requirement of the feed material is met. The high titanium content in the metal is due to over-reducing conditions in the furnace, which can be rectified by increasing the correction material feed rate. If the correction material feed rate is already at its maximum the carbon setting of the kilns can be reduced.

4. If the chemistry is satisfactory but the slag bath is expanding it means that the power/feed ratio is not correct. This scenario simply needs an increase in the mixture feed rate to the furnace.

5. If the chemistry is satisfactory but the bath is shrinking it means that the feed rate is too high for the available power. This situation can soon develop into an overcharged and crusted condition, which could start to influence the chemistry. In this case the furnace feed mixture rate should be reduced.

In most of the unbalanced scenarios that are experienced in the operation of the open slag bath furnace both the charging condition and the chemistry tend to be incorrect. This is due to the close relationship between these two aspects. There are also many ways of handling these scenarios, but there is expected to be an optimal approach that will yield the most rapid results. These situations (6, 7, 8 and 9 in Table 3) are discussed next.

6. The high titanium content shows that strongly reducing conditions prevail. An expanding bath also illustrates that the mixture feed rate is too low for the power input. The concentration of residual elements in the iron can be expected to increase and the tapping temperatures to be high. In this scenario it might be said that correction material must be increased or the carbon must be reduced, but with the eroding banks the furnace is not reacting to the feed mixture composition only since carbon-rich inner banks are being consumed (as described in section 2.4).

   The best cause of action would be to stabilize the feed banks by increasing the mixture feed rate. It is also important to adjust the millscale feed rate in order to keep the ore/millscale ratio as it was before the feed rate was increased. If, after the banks have been stabilised, the high titanium content persists, then the millscale feed rate can be increased.

7. This is considered to be an extremely dangerous situation, since the banks are attacked by a very aggressive slag: with the increase in FeO content in the slag (low titanium content), the slag melting point and viscosity are expected to decrease, causing more rapid erosion of the banks and the furnace lining. The bath is open which means that the furnace is influenced by both the kiln feed mixture composition and the inner refractory banks. This indicates that a carbon shortage is experienced (see section 2.4)

   The best cause of action would be to stop feeding of the correction material completely, and also to increase the feed rate to balance the current power setting. If the banks are stabilising but the low titanium content remains, an increase in kiln carbon can be made.

8. In this situation the titanium content is high, which indicates a highly reducing environment. The concentration of residual elements in the iron will also be high, consuming much energy. The energy input is therefore not sufficient to melt the feed mixture and the bath shrinks. The best way of dealing with this problem is to increase the feed rate of correction material. If the bath does not open up, there is no choice but to reduce the mixture feed rate in order to open up the slag bath.

9. The bath is shrinking and the metal titanium content is low. This means that reduction is incomplete and that the power is insufficient to match the mixture feed rate. This is an overcharged condition where the power input does not match the energy requirements of the feed mixture (including the energy requirement of reduction).

   The feed rate should be decreased so that the banks can stabilize at an open bath condition. Only once the banks have stabilised and the feed mixture is enters directly into liquid slag, should the chemistry be re-

evaluated and the necessary changes made to the correction material and carbon content.

2.8 Furnace characteristics and interpretation [15]

Ultimately a furnace control strategy must provide the operator and supervisors with a complete toolkit to control the product quality no matter what the scenario might be. Figure 15 below shows schematically how the furnace state can go through cycles of undercharged and overcharged conditions. Often over-compensating changes are made which disturb the furnace energy balance even further. Response times (e.g. a change in kiln carbon content takes several hours to reach the furnace) can also contribute to such oscillatory behavior.
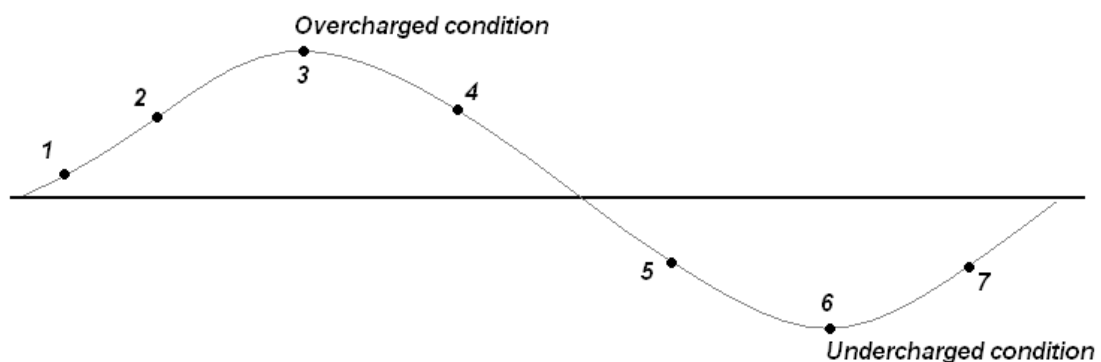
Figure 15: Illustration of possible cyclic changes in furnace condition with time.

Figure 15 schematically shows the extent of under-charging (distance below the axis) or overcharging (distance above the axis) with time (distance along axis.) Good decision making depends on knowing exactly where in such a cycle the furnace is. The furnace behavior related to these positions within the cycle will now be discussed in more detail.

1. The furnace is at a good condition with well established and stable feed piles. A soon as the feed rate becomes slightly higher than the power can consume, the furnace will start to cool down. The feed piles will grow towards the electrodes, not only because the feed rate has increased but also due to the reduction in superheat of the slag. This reduction in superheat will cause the feed mixture to dissolve more slowly. At this stage the tapping temperatures will start to become slightly lower, but no change in the furnace chemistry would be detectable yet.

2. The liquid slag inside the furnace is now unable to melt all the raw material. The un-melted material will lead to a "mushy" and "cold" slag which will make slag tapping difficult. Difficult slag tapping will be observed especially at the start of the tap, but will become better as more slag is drawn from the middle of the furnace. The furnace chemistry will start to change to a more oxidizing condition.

3. At the peak of the overcharged condition the furnace will start to develop crusts on top of the slag. The un-melted raw material will start interacting with the electrodes, which will cause erratic electrode movement and resistance. The banks will collapse due to slag undercut and cause incidents of severe gas evolution, with associated difficulty in gas plant control. The shell temperatures will slowly start to decrease as the entire furnace temperature decreases.

4. The overcharged condition will have been noticed by the operating personnel and compensated for by reducing the feed rate. The first priority is to liquefy the area around the electrodes and then melt the crusted feed banks. This approach will usually be continued until a change in conditions is observed. The temperature will not increase strongly until the un-melted feed material has been consumed. At that point no unmelted feed material is present to act as a coolant, leading to a sharp increase in the furnace temperatures which is specifically seen in the iron and slag tapping temperatures. Slag will flow very easily during tapping and tap hole drill depths will be short. An increase in reduction of the residual elements to the iron will be observed due to higher temperatures if enough carbon is present.

5. At this point the furnace will become undercharged if a low feed rate is maintained. The feed banks will be attacked by a very hot and fluid slag. This will increase the rate of reactions and lead to highly reducing conditions in the furnace. The feed banks will decrease in size and severe undercutting may occur which leads to frequent collapses. The electrode movement and resistance are stable but periods of furnace overpressure and gas plant control problems are experienced due to collapses of the banks. This is a period where good production tonnages are achieved and vanadium recovery is also high.

6. This period is marked by increased slag and iron tapping temperatures. The slag bath will be fully open and the feed piles very low. The drill depths are at their shortest and difficulty with closing tap holes may be experienced. The shell temperatures are at their highest as the freeze lining is eroded. This is an extremely dangerous period for the furnace as refractory damage may occur.

7. The operating personnel will eventually rectify the undercharged condition, typically by increasing the feed rate. Excessive increases in feed rate can again lead to a mushy slag condition, which usually cause slag tapping difficulties. A decrease in the extent of reduction of residual elements to the iron is also seen. Overcompensation would cause the furnace to move into its next overcharged condition, where the cycle starts again.

3. Principles of process control for the open slag bath furnaces

Controlling a metallurgical process such as the open slag bath furnaces is considered to be extremely difficult. The reason for this is mainly due to the two distinct sections of control that needs to be managed and integrated to not work independently of each other. These two sections can be classed as, first, well-defined parameters such as the electrical control of the furnace, and second ill-defined parameters such as reducibility of the ore, metallurgical memory of the furnace, coal quality and retention time through the process.[26]

Electrical control of the furnace is done with feedback control structures and works well, since the information is accurately available with very short time constants. The same feedback control however poses difficulty when working with processes that have long time constants such as electric furnaces. The best way to control these processes is by utilizing a system that allows feed forward control. In order to do this effectively a metallurgical database and advanced statistical control are necessary, to be able to respond to process raw material variations coupled with changing retention times and mixing scenarios. [26]

Although this project did not make use of such statistical control for the prediction of raw materials, it became clear very quickly that feedback control will only help control the process partially. The pivot point for the effective control of the furnace was shown to be the maintenance of the energy balance. All the systems that were developed, however primitive at this stage, focused on this single objective and will be built upon in future developments.

The following principles were followed to formulate the process control suggestion for this project.

3.1 Raw material classification

Highveld does not use a blending and reclaiming method for its different streams of raw materials. This does make it difficult to know exactly what the properties of the raw materials would be when these finally reach the furnaces. Currently the most basic form of feedback control is used where the metal and slag analyses are used to make changes to the raw material mixture at the very start of the process. A change such as this has an estimated time constant of 24 hours, which leads to very ineffective chemistry control.

Important raw material parameters are:

- *Coal* – fixed carbon, moisture content, volatile content, ash content, size distribution.
- *Ore* – vanadium content, iron content, titanium content, size distribution

Although the dolomite and silica quality do not vary as much and small amounts of these components are used, important aspects as listed below should also be monitored.

- **Dolomite** – moisture content, LOI (loss on ignition) and size distribution
- **Silica** – size distribution, $\%SiO_2$

This information must be captured in a database that classes the current raw material properties into different mixture batches based on the current mass contributions.

3.2 Kiln prediction model

This model uses the particular raw material mixture class together with operational variables such as rotational speed, feed rate, and temperature profile to predict the discharge chemistry, temperature and the very important pre-reduction value. This model could be based on regression analysis linked to a dynamic data base.

The flow of material between the raw material section, kilns and furnaces can be used to control feed rates and bunker levels in order to maximize throughput. Tracers can also be used to show where raw material batch changes are in the process.

3.3 Furnace mass and energy balance

The consistency of the furnace energy balance is the most important aspect that controls both productivity and product quality. A dynamic mass and energy balance is therefore required that takes into account the kiln discharge properties (which depend on both the initial raw material properties and the kiln operational settings). The energy balance can easily take information such as heat loss values, downtime scenarios and power utilization into account. This system ensures that the correct amount of mixture enters the furnace with the correct power input to maintain furnace balance at all times.

As soon as new metal and slag analyses become available a database will capture the information to make updates on the raw material and kiln operational predictions. In this way the system will become more and more accurate as more information is available. The accuracy of such a mass and energy balance database can be improved by introducing a technique such as data reconciliation. This technique assigns error margins to different streams of information and is derived based on the effect that a particular stream will have on the outcome of the balance. A sensitivity analysis is therefore done on the different information streams, where a stream that has a great impact on the final answer will have a small allowable error margin. Iterations are done to derive a final answer that will be used to change set points and therefore control the

process. A reconciled balance can also be used to identify measuring device failure, incorrect analyses and process irregularities by the difference in values before and after reconciliation.[27]

3.4 Objectives of process control

Although a system as briefly discussed above will not yield a perfect control with no variation in product quality, it will ensure that better-informed decisions are made more often. These systems, no matter how sophisticated, are only as good as their boundary conditions and will continually need human expertise. All metallurgical process control systems have the same objectives and are listed below:

- Optimize product quality
- Minimize energy consumption, or in general optimize environmental performance
- Optimize energy and material flow around the plant in order to optimize overall plant throughput.[26]

4. Problem statement, hypothesis and project objectives

In order for the open slag bath furnaces at Highveld Steel to perform optimally, the many variables that control the different aspects need to be understood and controlled within reasonable limits. It must also be understood that all these variables play an intricate part in the furnace stability.

4.1 Problem statement

The open slag bath furnaces at Highveld Steel require a control system which is able to keep the product quality within the desired limits and at the same time optimize production volume. This control system needs to be based on sound experimental work and at the same time be practical in its implementation. The work done in this project needs to pave the way for a rule based computer control system for all the open slag bath furnaces at Highveld Steel.

4.2 Hypothesis

The product quality and production volume (from a metallurgical view point) for the Open slag bath furnaces at Highveld Steel can be controlled simply by controlling the furnace charging condition and reducing state.

4.3 Project objectives

In order to address the problem statement and test the hypothesis, the following project objectives were addressed.

➢ Stabilize and maintain the general furnace energy balance which will result in

- o Consistent vanadium recovery (product quality).
- o Decreasing losses of metal to the slag.
- o Decreased metal sculling, so giving an increase in the iron yield.

➢ Better level of furnace predictability, therefore only disturbed by engineering downtime.

➢ Improved power consumption.

➢ Standardise decision making regarding furnace variables.

5. Project layout and experimental procedure

a)   The first step in the project was to develop a complete process mass and energy balance. The purpose of the energy balance is detailed below:

- To establish the effect of the kiln pre-reduction on the furnace energy requirement.
- Quantify the energy change when correction material is added in the form of millscale.
- Use the mass and energy balance to develop a systematic furnace charging program for different furnace conditions.
- Quantify the relationship between the furnace energy balance and furnace feed temperature.
- The effect of changes to the kiln flux settings on the slag basicity.

    The development of the mass and energy balance gave rise to the following additional work:

- Special kiln discharge samples cooled under argon gas for accurate carbon estimations. The following procedure was followed for this experiment:

    o A representative sample was taken from the kilns that provide feed to the open slag bath furnaces. Four samples were taken in order to test the repeatability of the results.
    o The kilns where samples were taken were set on the same feed mixture composition. This allowed easier comparison.
    o The samples were taken in a steel sample cup, which was fitted with a steel lid. An illustration of the sampler is shown in figure 16.
    o Argon gas was flowed through the sample cup with the sample inside. A positive pressure was maintained from the inside of the cup in order to displace the air.
    o The sample was cooled down under an argon atmosphere in order to keep the sample from oxidizing.
    o The samples were sent for analysis at an external laboratory. The purpose was to determine the oxidation states of iron and also the carbon content in the kiln discharge. The results are included in the appendix.
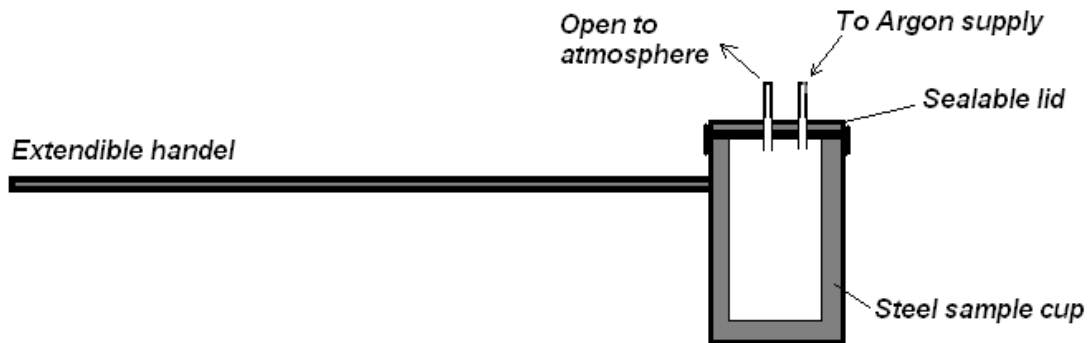
Figure 16: *A schematic illustration of the kiln discharge sampler.*

- Quenched slag samples to accurately determine FeO content. The following procedure was followed in conducting the tests:

  o One slag sample from two open slag bath furnaces was taken while the furnace was tapping.
  o These samples were taken by using a sample spoon made from high carbon steel.
  o The bottom half of the sample spoon was held in a bucket of water in order to cool the slag sample as soon as possible.
  o These samples were used to determine the amount of Fe relative to the amount of FeO in the slag.
  o The general chemical analysis was also compared to the results obtained from the Highveld laboratory.

- Determination of slag enthalpy by using the Fact Sage software package was performed.
- Heat loss calculations were done in order to establish the correct energy balance and develop the charging tables.

b) The next step was to develop a procedural system for controlling the furnace chemistry and charging condition. This step was extremely important since it helped in consistent decision making and therefore provided useful results which were vital for further control development. The two main components were:

- *Charging table* – these tables relate the correct feed rate to a specific power input and furnace charging condition. Additional work was required to determine the accuracy of the actual furnace screw feeders. The feed rate available to the plant personnel is a calculated value based on the volume displacement of one revolution of the screw feeder. The determination was done by using the mass balance to relate the total

estimated amount of ore feed by the screw feeders to the actual amount of iron produced for a period, was compared.

- *Furnace chemistry control* – the manipulated variables are the correction material addition, kiln mixture settings (coal, dolomite and silica). Here the optimal furnace conditions, which yield high vanadium recovery, were investigated first. Since the metal titanium content is indicative of the furnace reduction state, the titanium content was therefore related to the vanadium recovery. The control of the correction material feed rate and kiln coal setting needed to be quantified in an operational procedure to control the product quality.

c) The control system was evaluated to test the sensitivity of these furnaces to the control measures mentioned in (b). This evaluation looked at the following aspects:

- Product quality in terms of vanadium recovery.
- Chemistry stabilization.
- Power consumption expressed as kWh/t. This measure gave an indication of the success of maintaining the energy balance of the system.
- Furnace wall temperatures, which give a further indication of the energy balance stability.
- Furnace slag tapping temperature. The slag bath is used for melting the ore in these furnaces and not the arc itself. The slag tapping temperature therefore provided an indication of the stability of the energy balance and hence the reaction zone, which relates to product quality.

The data was continually compared to the period prior to implementation of the new control system, to assess the success of the project.

6. Results and discussion

6.1 Open slag bath process mass and energy balance

6.1.1 Heat loss through furnace wall and roof sections

The heat loss from the furnace was calculated to be 5.56 MW on average for the specific data set used. It is however less than the campaign average of approximately 7 MW mentioned in section 2. These calculations were done by using hourly data for March 2008 on furnace 1. The following equations, assumptions and constants were used.

- The furnace wall has three levels of thermocouples and each point is fitted with two thermocouples on different depths. This allows approximate heat loss calculation by using the Fourier heat conduction equation as shown in equation 13 below.[28] Steady state, one-dimensional conditions were assumed for these calculations. The exact thermocouple positions are shown in the appendix.

$$\frac{q_x}{A} = -\kappa \frac{dT}{dx}$$ …………………………………………………………… 13

The next step was to determine correct thermal conductivity values for the different sections of the furnace, as well as the surface area of heat conduction. These values were obtained from the supplier of the refractory material and are shown below in figure 17.
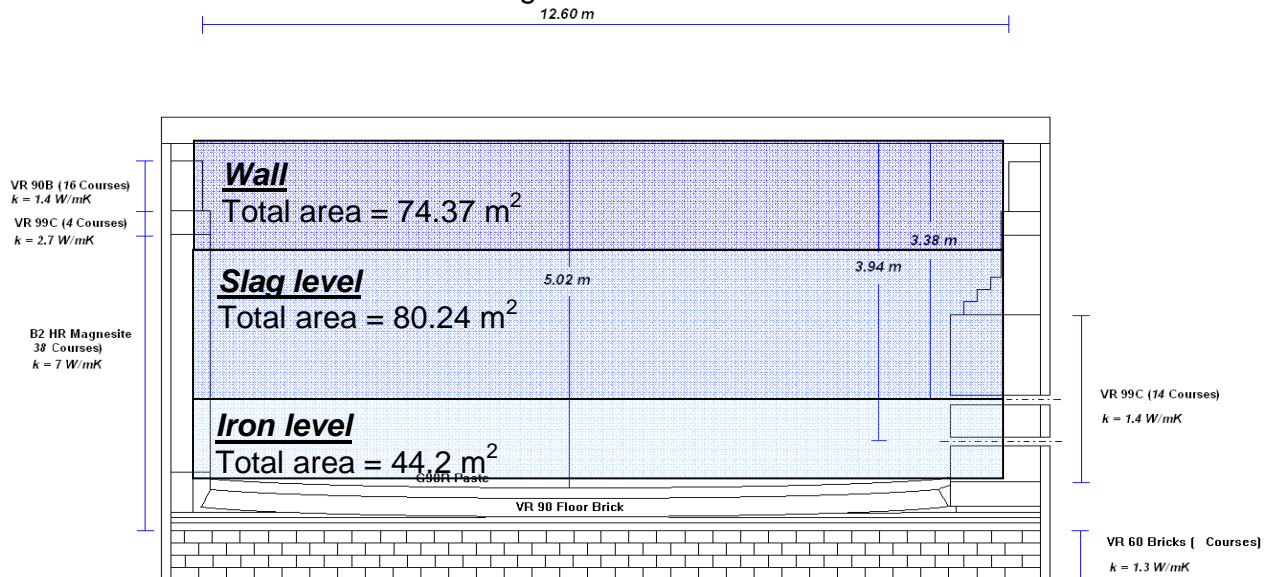
Figure 17: Important furnace dimensions and the different refractory zones with their thermal conductivity values and surface areas.

- The roof of the furnace consists of 23 panels with a refractory lining on the bottom side and water cooled cannels at the top sections. Figure 18 gives an illustration of the panel. These panels have different sizes, which are bolted together and make up the entire roof.
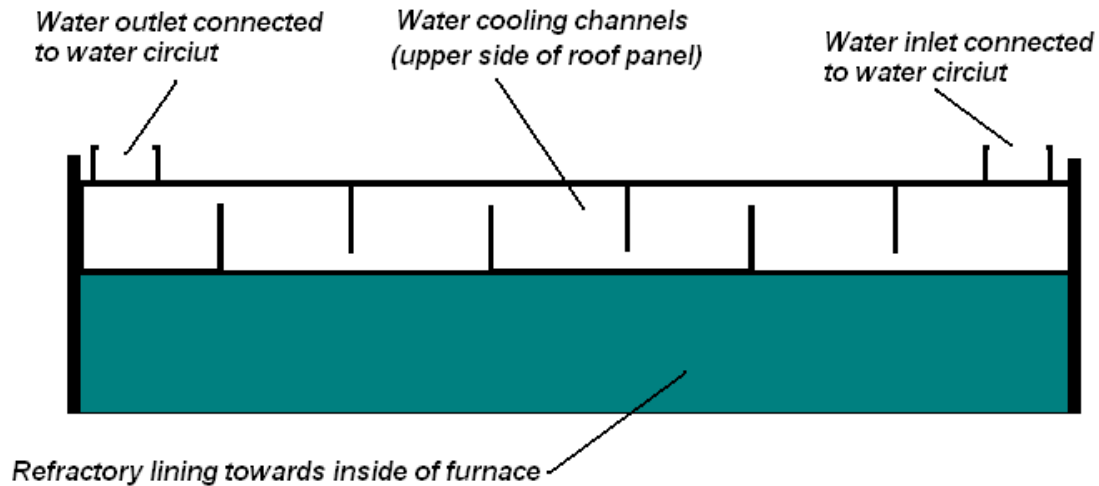
Figure 18: *Simple illustration of the furnace roof panels.*

The heat loss through the roof was calculated by using the enthalpy change of the water flowing through the panel. The water flow rates as well as the inlet and outlet temperature are recorded on an hourly basis.

Equation 14 was used to calculate the heat loss in MW.

$$\Delta H = C_p \, \Delta T \qquad\qquad (C_p = 75.438 \text{ J/gmol K}) \; …………………. \; 14$$

ρ_{water} = 1000 kg/m^3.
M_{H2O} = 18 g/mol

From the calculations the relative amount of energy that is lost through the different sections of the furnace was determined; results are shown in table 4. These calculations show that the average heat loss through the furnace wall and roof is 5.56 MW with a campaign maximum of 7.99 MW.

Table 4: *shows the percentage energy loss through the different areas of the furnace refractories.*

Roof	89.95%
Wall	1.79%
Slag	3.10%
Iron	2.15%
Hearth	3.01%

As expected the roof is the main heat loss path. It is interesting however, that the upper wall area has the lowest energy loss. It appears that the piles of feed material next to the wall successfully shield the upper wall from arc radiation.

The effect of furnace downtime and energy loss through the wall and roof was also investigated. Figure 19 shows a selected period where it is clear that the heat loss is affected significantly by the furnace utilization. It can therefore be said that the heat loss term in the furnace energy balance must be adjusted as the power input changes. The information on this graph has implications for the development of start-up procedures, for cases where the furnace was out for a significant period.
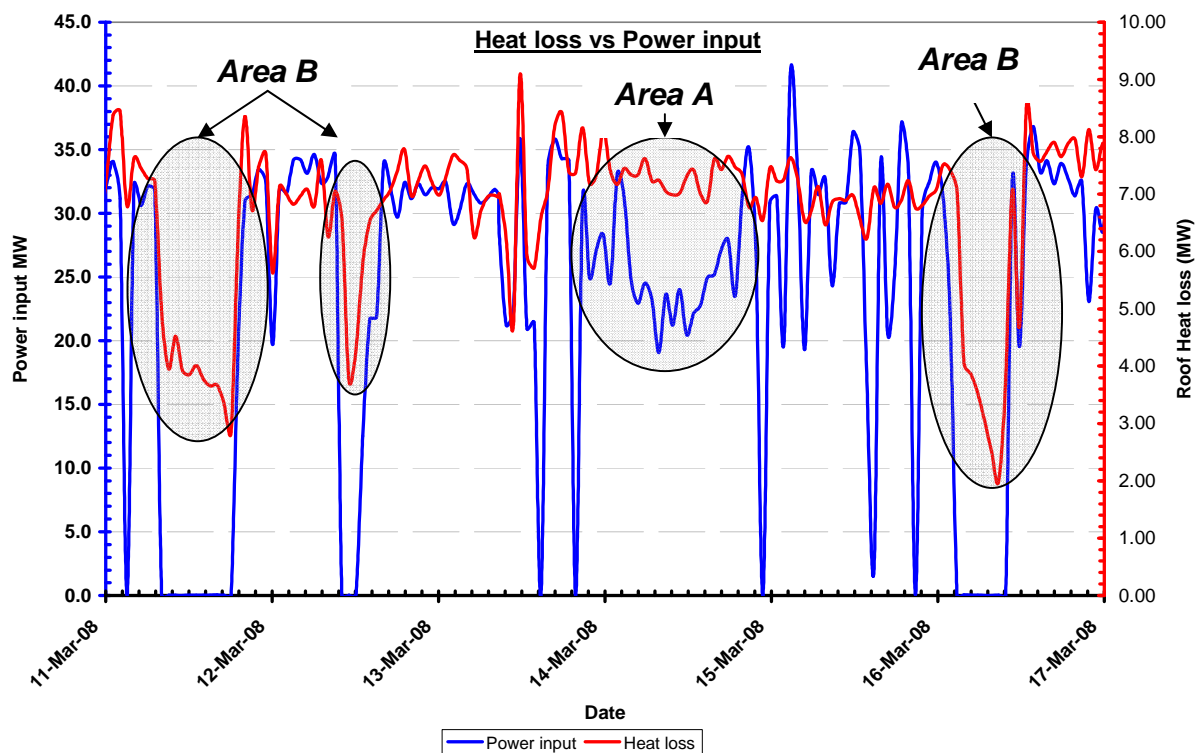
Figure 19: *Heat loss as a function of power input.*

Figure 19 shows periods when the furnace merely reduced power input and was not switched out completely (Area A). The heat loss in these periods remained largely unaffected. It is also seen that when the furnace was switched out completely the heat loss dropped off quickly (Area B). This phenomenon emphasizes the difference in energy consumption between the open slag bath furnace and the submerged arc furnace (in the latter case the arc is shielded by the furnace burden).

6.1.2 Complete process mass and energy balance

Below is a process mass and energy balance summary. The complete input and output data are available in the appendix. This summary is done for the following conditions:

- 36 MW operation.
- No correction material addition.
- 550 °C furnace feed temperature.
- Gas volume in the summary calculated to be at atmospheric pressure.

Table 5: shows a summary of the furnace mass and energy balance

Mass balance summary				Energy balance summary		
Total effective mass into kiln	1372.6	kg		Energy reqiured for kiln process	0.76	kW
Iron in	485.6	kg		Furnace feed temperature	550	°C
Fluxes in	149.3	kg				
Pe-reduction	40%	%		Slag tapping temperature	1460	°C
Metallization	17%	%		Metal tapping temperature	1360	°C
Ash in coal	16%	%		Gas exit temperature	1000	°C
Ore	73.5%	%		Energy requirement per ton of furnace feed	535.9	kW
Dolomite	6.1%	%		Energy requirement per ton of kiln feed	1.0	MW
Silica	0.0%	%				
Coal	20.4%	%		kWh/ton of metal	1656.0	kWh/t
				Iron produced per MW	0.820	t/MW
Carbon required for pre-reduction	61.1	kg				
Carbon burn away in kiln	154.4	kg		Millscale energy reuirement	994	kWh/t
Carbon required for pre reduction	30.2%	%		Fine ore energy requirement	1122	kWh/t
Carbon burn away kiln	14%	%				
Kiln air requirement	285.2	kg				
Total mass into furnace	1073.0	kg				
Correction material added	0.0	kg				
Fe into furnace	45.3%	%				
Fe into furnace	485.6	kg				
Slag produced	382.5	kg				
Slag basicity	1.87					
Metal produced	471.6	kg				
Iron superheat	178.0	°C				
Gas produced	216.6	kg				
Gas produced	173.2	Nm³				
Metal/Slag ratio	1.2					
Iron tapped/furnace feed ratio	0.44					

The following is a list of assumptions and calculation procedures for the mass and energy balance:

1) Carbon combustion was calculated to be the difference between incoming carbon units (into the kiln) and the sum of the carbon that reports to the gas phase and the metal in the furnace. It is also assumed that this carbon loss only occurs in the kiln process, except for a very small amount accounted for in assumption 5 below. In a dynamic process control balance this value will be

updated to maintain the calculated carbon content in the metal similar to the actual analysis.

Chemical analysis of the kiln discharge samples, showed that approximately 15% of carbon remains after the kiln process. This value corresponds better to the mass balance than the Highveld lab predictions, but is slightly higher than what the mass balance predicts.

2) A 5% kiln spillage is assumed and subtracted from all the streams before pre-reduction was calculated. This spillage is discarded and not recycled into the process.

3) The correction material is assumed to have the same analysis as the ore.

4) It is assumed that only iron oxides are reduced in the kilns. The pre-reduction hence refers to oxygen removal from iron-oxygen compounds only. The O/Fe molar ratio of the unreduced kiln feed is approximately 1.38, while the ratio after pre-reduction is calculated to be 0.83.

5) The partitioning factors for all elements were back-calculated from a typical analysis and then used as an input for the mass balance. In a dynamic process balance used for control, these values will continually be back-calculated based on the slag, metal and gas analysis.

6) The furnace off gas analysis was used to calculate the CO_2 content. These live analyses are available from an online gas analyzer after the gas is quenched in the venturi system. The following species are recorded: H_2, O_2, CO, CO_2 and N_2. It was assumed that the difference between the incoming O_2 and the outgoing O_2 is used to produce CO_2 through carbon and carbon monoxide combustion.

7) The N_2 content in the furnace off gas analysis was used as the tie element to back-calculate the furnace air ingress, since no nitrogen is assumed to be carried by the kiln feed.

8) The kiln air off gas was not included in the mass and energy balance, since it is not of any interest for this project to accurately calculate the kiln energy requirement. The important aspect around the kiln balance is the material transfer into the furnace.

9) The ash yield represents the amount of ash that is carried through the process and repots to the slag, where the remainder is lost through the kiln and furnace off gas system. This value was calculated to provide similar slag basicity as seen in the actual process. Actual ash yields are not available and must be calculated based on the above assumptions.

The Sankey diagram was drawn by using the mass and energy balance as follows:

- The pre-reduction was set to be 0% and all input and exit material temperatures were changed to be 25°C. The only energy demand for the process is therefore assumed to be that of reduction.
- The kiln pre-reduction was adjusted to be 40% and the energy requirement change noted.
- The furnace feed mixture temperature was changed to 550°C and the energy requirement change noted.
- The slag and iron exit temperature were adjusted one after the other to be 1460°C and 1360°C respectively and their effect on the energy requirement noted.
- The gas exit temperature was adjusted to be 1000°C and its effect on the energy requirement noted.
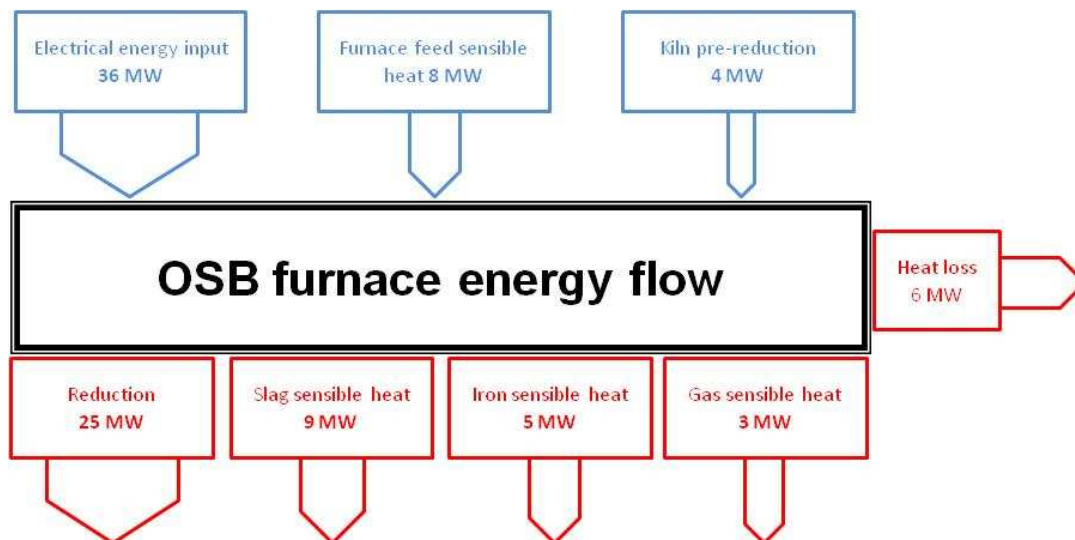
Figure 20: shows a Sankey diagram illustrating the flow of energy through the process.

6.1.2.1 Slag enthalpy calculations.

The enthalpy of slags cannot be calculated by simply adding the individual enthalpies of the compounds which make up the slag. This would mean that the heat of solution would be neglected. In the case of slags and also liquid iron with saturated levels of carbon and silicon, the heat of solution cannot be neglected, unlike in the case of gas, because the activities of the slag components depart substantially from ideality.

FactSage can be used to calculate the slag enthalpy, but it is more convenient if an Excel-based method were available for this. The approach of Björkvall[29] can be used to find the enthalpy of SiO_2-Al_2O_3-CaO-FeO-MgO-MnO slags within

Excel, but does not include parameters for TiO_2 and Ti_2O_3. One approximation is to calculate the enthalpy of the slag – but excluding TiO_2 and Ti_2O_3 – with the Björkvall approach, and then to assume that liquid TiO_2 and liquid Ti_2O_3 mix ideally with this mixture. The enthalpies of the liquid titanium oxides were taken from the literature compilation[30] as also used within FactSage.

In both cases – with this approximate procedure and with the FactSage approach – the slag composition was normalized as follows: Cr_2O_3 and sulphur were excluded; V_2O_5 was recalculated as V_2O_3, and the V_2O_3 was taken as Ti_2O_3 for the energy balance (this was necessary because the FactSage slag model does not include V_2O_5)

From this comparison, the combined Björkvall-ideal-mixing approach gave values which were only slightly larger (by approximately 0.3%) than the FactSage values, which confirmed the utility of this approach. It was also confirmed that the slag enthalpy is not a strong function of the trivalent titanium content of the slag.

The slag analysis showed that the average FeO content of the OSB slag is 8.1%, which includes both metallic Fe and FeO. This is well above the mass balance calculations of 2.7% FeO. These results can be seen in the appendix.

6.1.2.2 Furnace energy requirement as a function of pre-reduction and correction material addition.

The kiln pre-reduction is variable, based on changes in kiln operational conditions. Millscale is used to correct over carbon conditions. Both these variables affect the energy balance and their effect was quantified. Knowledge of these effects allows the furnace feed rate to be adjusted to maintain a constant power input of 36 MW. Table 6 shows this relationship expressed as a percentage change from the normal operation. This normal operation is considered to be 40% pre-reduction and 0 t/hr correction material with 36 MW electrical supply. The furnace feed molar O/Fe ratio is typically 0.83 and is assumed that pre-reduction only refers to iron oxides.

Table 6: Required feed rate adjustment as a function of kiln pre-reduction and correction material addition rate.

		Correction material (t/hr)						
		0	1	2	3	4	5	6
Pre-reduction	30%	-3.9%	-5.9%	-7.8%	-7.8%	-9.8%	-9.8%	-9.8%
	35%	-2.0%	-3.9%	-3.9%	-5.9%	-5.9%	-7.8%	-7.8%
	40%	0.0%	-2.0%	-2.0%	-3.9%	-3.9%	-5.9%	-5.9%
	45%	2.0%	2.0%	0.0%	-2.0%	-2.0%	-3.9%	-3.9%
	50%	5.9%	3.9%	2.0%	2.0%	0.0%	0.0%	-2.0%
	55%	9.8%	7.8%	5.9%	3.9%	3.9%	2.0%	0.0%
	60%	11.8%	11.8%	9.8%	7.8%	5.9%	5.9%	3.9%

6.1.2.3 The sensitivity of the furnace energy balance to furnace feed mixture temperature.

Although the furnace feed mixture temperature cannot be controlled at this stage it is interesting to see how sensitive the system is to this. This temperature is a strong function of the time that the mixture spends in the furnace bunkers. If this time can therefore be controlled, by having a material flow management system, a consistent temperature can be maintained. Table 7 below shows this relationship for a constant 36 MW electrical supply. It is seen from the energy balance that a 100°C change in the furnace feed mixture temperature makes a 3.2% change in energy consumption (kWh/t) for a particular set of energy balance inputs.

Table 7: *Required furnace feed rate change for changes in feed mixture temperature.*

Furnace feed temperature (^{o}C)	Feed required (t/hr)	% change
400	43.6	*-7.2%*
450	44.8	*-4.7%*
500	45.8	*-2.6%*
550	47.0	*0.0%*
600	48.4	*3.0%*
650	49.8	*6.0%*
700	51.2	*8.9%*

6.1.2.4 Furnace tapping schedule.

A furnace tapping schedule was proposed based on the mass accumulation calculated by the mass balance. Since this model did not add any value and was never implemented, it is not discussed in much detail. The model needs an integrated system, which uses actual furnace inputs linked to a mass balance spread sheet. Only when this capability is obtained the model will be developed further. It is included in the appendix for purposes of future reference. This type of tapping model can help to maintain the furnace metal bath level, which is essential for logistical reasons in terms of ladle control. This model will only become active once improved data collection and calculation capabilities become available.

6.1.2.5 Kiln flux adjustments as a function of coal setting.

The kiln coal setting is adjusted as often as necessary to try to compensate for the increase and decrease in reduction state of the furnace. A coal change tends to take approximately 24 hours to show its effect, which makes it an extremely slowly reacting system. The coal setting is adjusted without changing any of the other flux settings. Table 8 and figure 21 below shows how the dolomite setting

should be changed in order to maintain a slag basicity of 1.85, calculated as $(CaO + MgO)/SiO_2$.

Table 8: *Flux addition adjustments at different kiln coal settings.*

Coal *(kg/t ore)*	350	370	390	410	430	450	470	490	510
Dolomite *(kg/t ore)*	200	210	215	220	225	230	235	240	245
Silica *(kg/t ore)*	19	21	21	21.5	21.5	21.5	22	22	22

It can be seen from table 8 that the silica setting can be kept almost constant while the dolomite setting is varied according to the coal setting. The coal setting is often required to be increased to 550 kg/ton and sometimes even higher which indicates poor quality coal. Figure 21 shows that the flux addition, specifically the dolomite setting, should be changed as the coal setting is varied.

Kiln flux settings as a function of coal

Coal setting (kg/t ore)
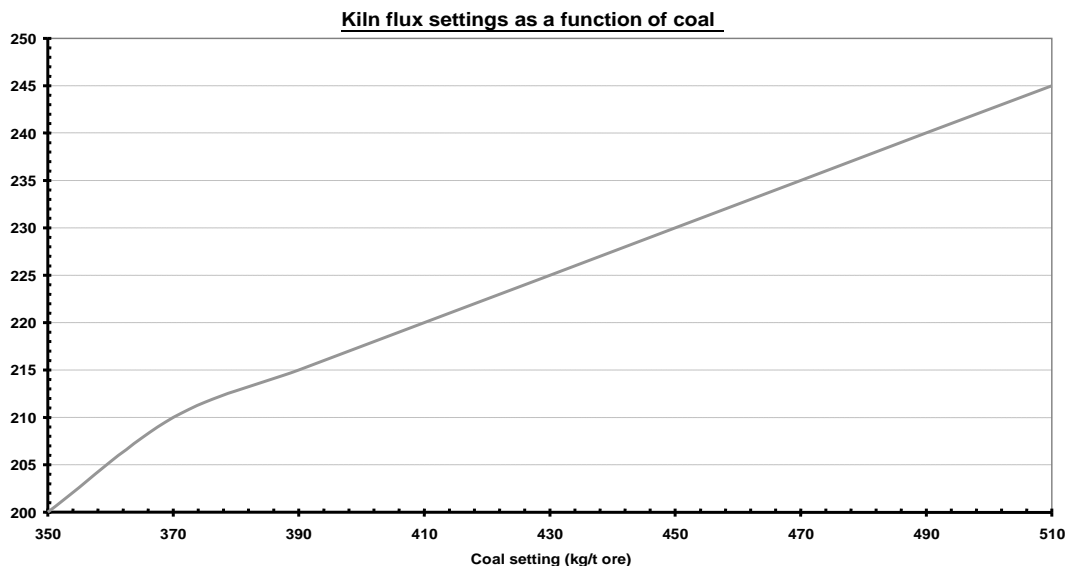
Figure 21: *shows that the kiln dolomite setting needs to be adjusted as the coal setting is adjusted, to maintain the slag basicity.*

6.2 Operational procedures

6.2.1 Furnace charging tables

Based on plant experience, supported by the mass and energy balance, charging tables were developed for each furnace (see table 10 below). These tables are strictly followed by each operator, in order to match the power input with the correct feed rate and hence maintaining the furnace energy balance. These tables are calculated form a simple power/feed ratio. The ratio was obtained from practical furnace experience and is shown in table 9 for various furnace conditions.

Table 9: *Actual power/feed ratio (MW/[t/h]) for various furnace charging conditions.*

Severely undercharged	0.49
Undercharged	0.55
Slightly undercharged	0.58
Good condition	0.62
Slightly overcharged	0.67
Overcharged	0.72
Severely overcharged	0.85

The required power input is calculated as shown in equation 13 below.

Power (MW) = **furnace feed rate** (t/hr) x **ratio + heat losses** (MW)…………….13

It can be seen that for each furnace feed rate a different MW value is obtained which corresponds to a particular furnace condition. The evaluation of the furnace condition is the only variable that is affected by the decision making of the furnace operating personnel.

The plant material flow is managed by following a typical thought process as outlined below:

- What is the combined kiln feed rate of the kilns that can supply a particular furnace (value A)?
- Multiply this value by 70%, which is considered to be overall kiln material yield plus some contingency stock.
- Look for this value on the charging table in the feed rate row.
- Choose a suitable furnace charging condition and read the corresponding power input from the table.

If this procedure is followed the furnace will match the power with the feed as well as optimizing the material flow through the plant. A typical charging table is shown as table 10 below.

Table 10: *Extract from furnace 1 charging table. Feed rates are in t/h. The values in the table give the required furnace power Shaded areas are where the required power exceeds the furnace capacity.*

Table A – Furnace 1   Date changed: 18 April 2008

Furnace feedrate →	57	56	55	54	53	52	51
Severely undercharged	35	34	34	33	33	32	32
Undercharged	38	37	37	36	36	35	35
Slightly undercharged	39	39	38	38	37	37	36
Good condition	42	41	40	40	39	39	38
Slightly overcharged	44	44	43	42	42	41	40
Overcharged	47	46	46	45	44	44	43
Severely overcharged	54	53	52	52	51	50	49

Furnace feedrate →	50	49	48	47	46	45	44
Severely undercharged	31	31	30	30	29	29	28
Undercharged	34	34	33	33	32	32	31
Slightly undercharged	36	35	34	34	33	33	32
Good condition	37	37	36	36	35	35	34
Slightly overcharged	40	39	39	38	37	37	36
Overcharged	42	42	41	40	39	39	38
Severely overcharged	48	48	47	46	45	44	44

Furnace feedrate →	43	42	41	40	39	38	37
Severely undercharged	28	28	27	27	26	26	25
Undercharged	30	30	29	29	28	28	27
Slightly undercharged	32	31	31	30	29	29	28
Good condition	33	33	32	32	31	30	30
Slightly overcharged	35	35	34	33	33	32	32
Overcharged	37	37	36	35	35	34	33

The furnace screw feeder accuracy is an important aspect when the plant mass balance is developed. As mentioned earlier, the feed rate indicated on the furnace PLC is a calculated value based on a volume displacement for each revolution of the screw feeder shaft, and is verified by calibrating the kiln skips with a test weight. The screw feeder integrator readings however show a different value when compared with the iron tapped. These sets of data were compared for the month of March 2008 for furnace 6. The average iron content in the furnace mixture is calculated to be 45.5% by the mass balance, and this is assumed to be correct. The iron tapped is the primary product of the iron plant and is therefore considered to be accurately measured.

Table 11: *Comparison between the furnace feed and the actual liquid iron production for 6 months.*

Period	Iron tapped	Ore mix input *(tons)*	Fe in *(tons)*	Error
02/03/08 - 10/03/08	3790.4	6330.9	2867.9	24%
11/03/08 - 20/03/08	3397.6	5234.5	2371.2	30%
21/03/08 - 31/03/08	4516.8	6584.0	2982.5	34%
				30%

Table 11 reveals that the amount of furnace mixture that is thought to be fed into the furnace is likely to be 30% too low. If the feed control system on the PLC has a set point of 45 t/hr, the screw feeders are actually delivering 58.5 t/hr. The latter value is consistent with the energy balance, which is predicting 58 t/hr for 36 MW operation. These calculations can however be cross checked by looking at the actual plant power consumption (kWh/t). The power consumption is

fundamentally determined by the production rate of the plant or furnace. The most accurately measured value in any plant would obviously be its product mass, and can therefore be used to back calculate the amount of feed which will yield this amount of iron. The mass and energy balance shows a value of 1478 kWh/t iron, while the actual power consumption is in the region of 1972 for June 2008. The power consumption rate is however a strong function of energy losses and also the furnace feed mixture temperature. In order to reach a similar power consumption rate as the actual plant data, the following settings were assumed:

Table 12: *The main M&E balance variables that yield power consumption closer to the actual plant value.*

Avg power input (MW)	29.5
Feedrate (t/hr)	35
Total energy losses (MW)	9.5
Furnace feed temperature (^{o}C)	400

It can be seen that the total energy losses are much higher than what the average heat losses were calculated to be if closer to actual power consumption values need to be obtained by the mass and energy balance. It is therefore assumed that other losses occur elsewhere in the process.

From the process mass and energy balance it was established that one ton of millscale is equivalent (in energy requirement) to approximately 1.5 tons of kiln product, while fine ore is approximately 11.4% more energy intensive than millscale. This is a significant aspect, since when correction material is added for chemistry control the amount of furnace feed reduction must be calculated. The instruction is to subtract 1.5 tons of kiln mixture for every one ton of correction material (millscale) that is added. The large difference in the energy requirement of the kiln mixture and the correction material is simply due to the much higher sensible heat of the kiln product (approximately 550°C), and its pre-reduced state, compare with the unreduced correction material which is fed at room temperature.

6.2.2 Furnace chemistry control

The optimal titanium content that will yield sufficient vanadium in the metal needs to be determined. Figure 22 shows actual vanadium content in the iron together with titanium content for the same sample. It can clearly be seen that the vanadium is generally above 1.2% whenever the titanium is below 0.2% (area A), and the reduction of vanadium drops to extremely low levels when the titanium is low (area B). The latter condition usually occurs when the furnace carbon content is low due to a completely empty furnace (no feed piles visible), low-reactivity coal is used, or if there is a low coal setting on the kilns. The feed piles play an important role in the furnace reduction process, since excess carbon is contained

in the feed banks inside the furnace. It is very often experienced that when the furnace is without feed banks, the chemistry is also lost.
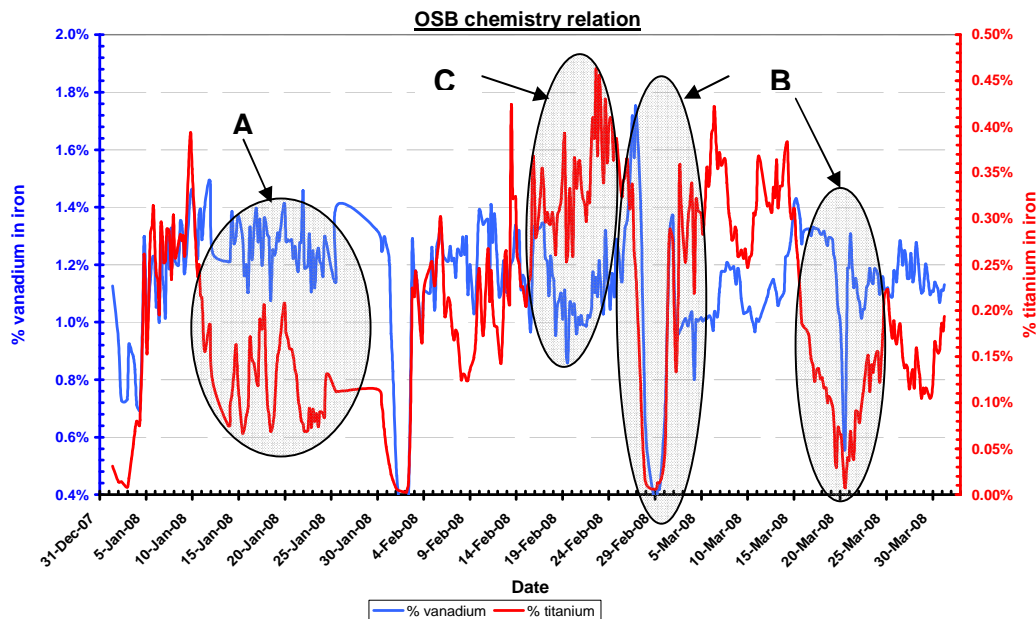
Figure 22: *Relationship between vanadium and titanium contents in the liquid iron.*

The current procedure instructs the operator to add correction material whenever the latest iron chemistry shows a titanium value above 0.20%. By doing this, considerable periods with good consistent vanadium reduction are maintained. In periods when very high titanium reduction is seen, the vanadium recovery tends to be reduced (area C). This is typically an over reduced furnace where difficulty in slag tapping and cold furnace conditions are experienced. In such a case, the coal setting is systematically reduced to lower levels. It appears that a lower temperature leads to preferential reduction of titanium rather than vanadium. The reason for this is not clear, but it appears not to be a simple thermodynamic effect: the reaction $V_2O_3 + 2Ti = Ti_2O_3 + 2V$ has a heat of reaction of -304 kJ/mol at 1500°C (value from FactSage), if all species are taken as pure solids. This exothermic reaction should hence be favored by a lower temperature, not suppressed by a lower temperature as the plant observations indicate. There might be a kinetic limitation to lower-temperature reduction of vanadium oxide.

A fine balance between low enough titanium levels in the iron (as a proxy for maintaining the right temperature), and high enough titanium reduction (indicative of conditions which are sufficiently strongly reducing) must be maintained. This balance seems to be between 0.15% and 0.20% titanium. Above 0.2% Ti an over-reduced condition is seen (low iron production rates, but often high vanadium contents) and below 0.15% Ti an under-reduced conditions is seen (low vanadium recovery but high iron melting rates). Both aspects need to be optimized.

6.3 Evaluation of the success of the control system

6.3.1 Vanadium recovery and chemistry stability

In order to evaluate the success of the control of the power/feed ratio, data from furnaces 5 and 6 were used. The data were gathered over a period which included the old operational system (September 2007 – December 2007) and a period where the new control was used (January 2008 – March 2008).

Table 13 shows these results. The average vanadium, carbon and silicon contents are shown for the old and the new systems respectively. The minima and maxima were also calculated for these periods. The standard deviation is calculated to quantify the chemistry stability of the furnace in these periods.

Table 13: Chemistry stability and average for the old and new control systems.

Furnace 5				
Old	**%C**	**%V**	**%Ti**	**%Si**
Avg	3.97%	1.17%	0.20%	0.16%
Std Dev	0.28%	0.13%	0.10%	0.06%
New	**%C**	**%V**	**%Ti**	**%Si**
Avg	3.76%	1.18%	0.13%	0.13%
Std Dev	0.31%	0.15%	0.07%	0.06%

Furnace 6				
Old	**%C**	**%V**	**%Ti**	**%Si**
Avg	3.81%	1.12%	0.25%	0.21%
Std Dev	0.34%	0.14%	0.09%	0.06%
New	**%C**	**%V**	**%Ti**	**%Si**
Avg	3.73%	1.13%	0.15%	0.15%
Std Dev	0.32%	0.20%	0.09%	0.06%

It can be seen that vanadium recovery for both furnaces 5 and 6 increased slightly with the introduction of the new control system. This increase might seem slight, but with the current ferro-vanadium price as high as $ 85 per kilogram it translates into substantial increases of revenue per ton of iron.[31] More importantly it is seen from table 13 that the titanium standard deviation has reduced and stayed the same for furnaces 5 and 6 with the new control procedures; the titanium recovery has also been lowered (which is a beneficial effect). This is indicative of a more stable process which relates to a stable energy balance. The apparent improvement in the vanadium recovery and chemistry stability is however severely affected by the engineering availability of the furnaces as well as the raw material quality.

6.3.2 Furnace power consumption

An important monthly furnace performance measure is the power consumption, calculated as kWh/ton of metal tapped. This aspect was mentioned at the beginning of this document to be one of the technical challenges for the open arc furnace. Since the inception of the new control system an average of approximately 200 kWh was saved per ton of liquid metal, compared with the old system of controlling the furnace. These results are shown in table 14.

Table 14: *shows the actual power consumption values for the two Open slag bath furnaces comparing the old and new control systems.*

Furnace	Old control (kWh/ton)	New control (kWh/ton)	Saving (kWh/ton)
5	2319.7	2133.6	186.1
6	2153.6	1931.6	222

The values in table 14 are considered to be very high, but are so due to a large data sample which includes periods of extremely poor production rates. The furnace power consumption is seriously affected by engineering availability due to larger than normal energy consumption during start-up procedures. Figure 23 shows this relationship graphically. The data were taken from furnace 6 for the last 7 months. It can clearly be seen that when the furnace is utilized 75%, a substantial improvement is shown in power consumption. This is due to lowered heat losses, and also better production stability. The entire furnace and its contents are kept hot during longer periods of high availability which impacts strongly on production rates.
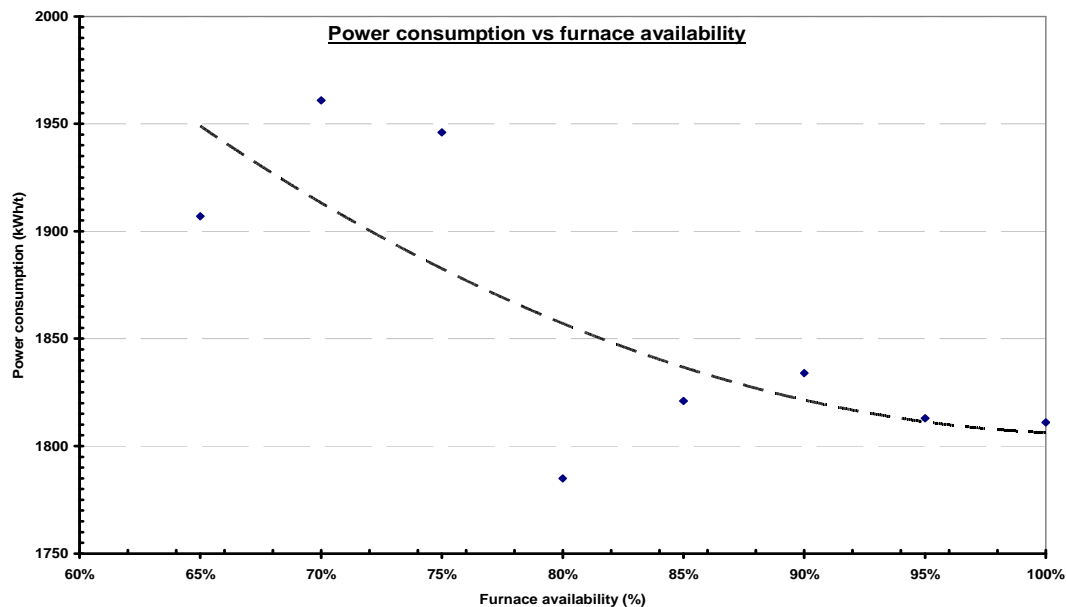
Figure 23: *The effect of furnace availability on power consumption for the open slag bath furnaces.*

6.3.3 The effect of the control system on the furnace wall temperatures

The slag level thermocouples were used to investigate the effect of the new control on the shell temperatures. From figure 24 it can be seen that a consistent cycle is still visible, even after the new control was established (indicated by the broken line). Since the wall thermocouple is fixed in one position, the furnace wall temperature cannot be expected to stabilize without long periods of consistent power levels, coupled with a balanced furnace feed. Even with the new control, the power/feed ratio is simply controlled but still with fluctuating power levels. This leads to the fluctuating wall temperatures as seen in the figure below.
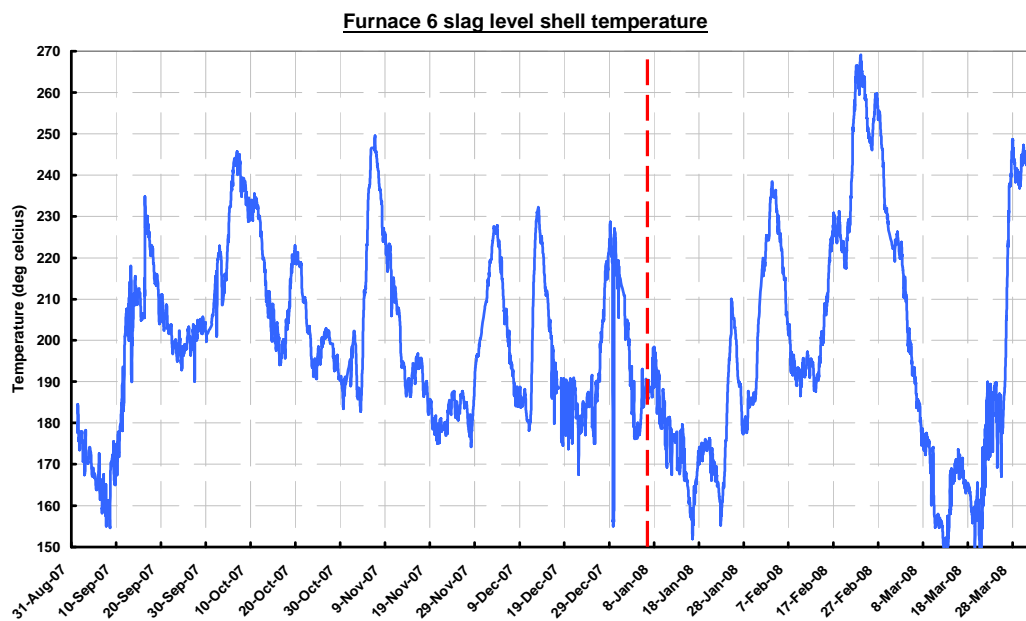
Figure 24: *Furnace slag level average thermocouple temperature, which reveals the furnace temperature cycle. The broken line indicates the time at which the new control system was introduced*

6.3.4 The effect of the control system on the slag tapping temperature

In the open slag bath process the electrical arc that is struck between the liquid slag bath and the electrode tip is generating extremely high local temperatures. It is however not the arc temperature that is responsible for the melting of the mixture but rather the slag bath. The furnace feed mixture in turn cools down the slag bath and thus would the slag temperature gives an accurate indication of the maintenance of the general furnace energy balance. The average and standard deviation of the slag tapping temperatures are again compared between the old and new control periods. Table 15 shows these results.

Table 15: *Slag tapping temperatures for furnace 5 and 6, comparing the old control period with the new period.*

Furnace 5 slag temperature		
	Old	New
Average (^{o}C)	1437	1442
Std Dev (^{o}C)	41	34

Furnace 6 slag temperature		
	Old	New
Average (^{o}C)	1439	1448
Std Dev (^{o}C)	33	24

It can be seen from table 15 that the average slag tapping temperatures are higher in the new control periods. This would result in higher iron temperatures, which in turn result in lower iron yield losses and better iron quality. The standard deviation for the new control periods on both the furnaces is also smaller compared with the old control period.

Highveld employs a contractor who recovers metallic pieces from the slag through a crushing, screening and magnetic separation plant. They have reported that approximately 5% metallics are found per ton of slag originated from the submerged arc furnaces whereas values lower than 3% are recorded for slag from the open slag bath furnaces. These reports support the suggestion that improved separation between the slag and metal would occur due to increased temperatures in the OSB furnaces.

6.4 Practical slag considerations

There are a few fixed ratios in the current Highveld slags, which are determined by the typical ore analysis. These fixed ratios were assumed, in order to calculate the change in specifically slag TiO_2 content as a function of basicity.

- ***TiO_2/Al_2O_3*** = 2
- ***CaO/MgO*** = 1.3

The basicity will be considered as the main variable as seen from the literature discussed in section 2.5.3. Table 16 below highlights the range of slag compositions that will most probably provide us with the best properties for our operation.

Table 16*: Typical slag composition range that is likely to yield the best properties.*

TiO2	25.0	30.0	35.0	40.0	45.0
Al2O3	12.5	15.0	17.5	20.0	22.5
CaO	21.9	19.3	16.6	14.0	11.4
MgO	16.8	14.8	12.8	10.8	8.8
SiO2	23.8	20.9	18.1	15.2	12.4
Basicity	1.63	1.75	1.92	2.19	2.714
CaO/SiO2	0.92	0.99	1.08	1.24	1.52

It can be seen that the TiO_2 content is influenced by changes to the other flux additions. The basicity in each case was adjusted to obtain a maximum of 15% difference between the sum (CaO + MgO), and SiO_2. As the TiO_2 content increases the cost associated with the slag would decrease, due to these two considerations:

- Less fluxing agents are required, which reduce the cost of raw materials, and
- Slag bulk becomes less, which in turn decrease kWh/t.

Figure 25 shows that a thick and difficult-to-tap slag caused operational problems as soon as the basicity increased to values above 2. Taking this in consideration the two slag compositions shaded gray in table 16 would be considered the best slag to produce.
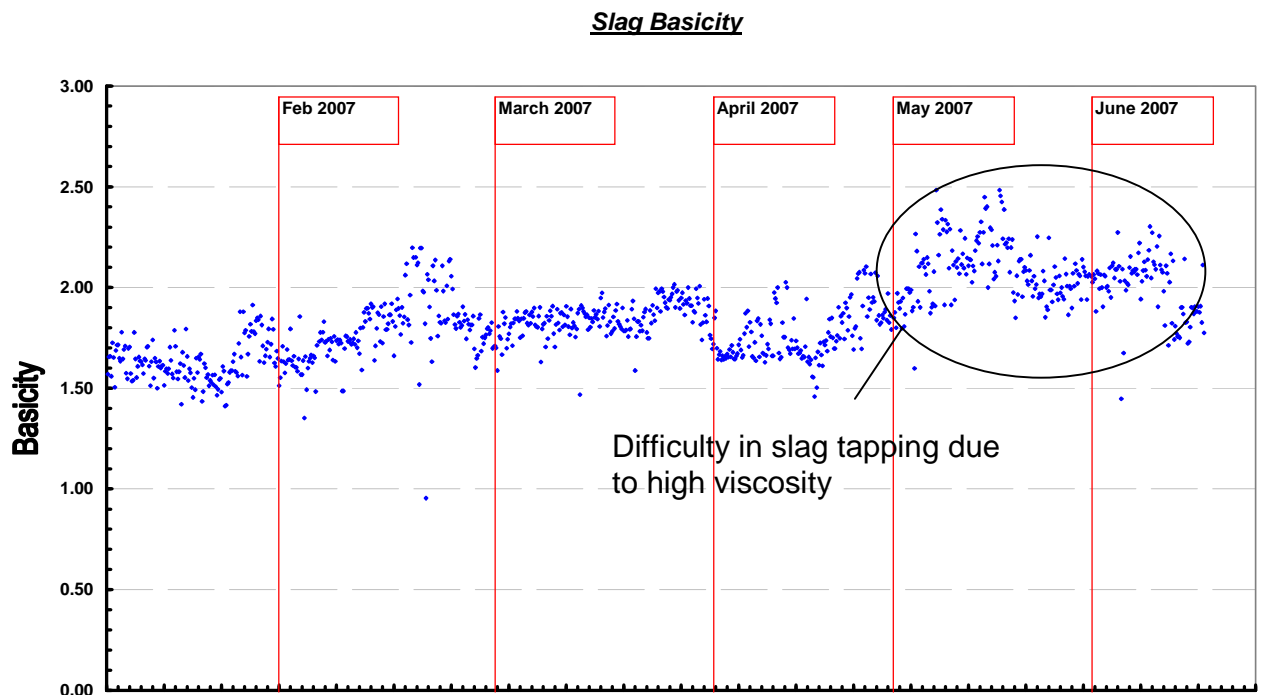
Slag Basicity

Figure 25: *The steady increase in basicity experienced on furnace 6 from the 1st of January 2007.*

Practically it was observed that as long as the slag basicity does not increase to values above 2, the slag viscosity is easily controlled by keeping the slag bath hot. As soon as slag tapping becomes difficult, the operators cut back on furnace feed, which effectively causes the bath to open slightly. This causes the slag to become hotter and hence eliminates difficulty in tapping the slag.

This practical observation is consistent with the theory discussed in paragraph 2.5.1 which states that perovskite is likely to precipitate at higher CaO levels and hence higher basicity, and result in an increase in slag liquidus temperatures.

6.5 Practical furnace operation and charging condition prediction

It has become clear that the furnace charging condition and hence the energy balance of the system can easily be predicted by other furnace parameters instead of physical furnace inspections. The parameters that show very close relationships with the charging condition observations are:

- Roof heat loss, and
- Power input stability.

We know from basic science that if excess energy is supplied to a system it will result in the increase of temperature of either the system itself or its surroundings. The same happens to the furnace roof from where the heat loss

value is calculated. This heat loss value is calculated as follows, based on the original Hatch design and proposed PLC calculations:

Roof heat loss panel $_i$ = 4.187 x (T_i – T_{151}) x Fe_i/3.6

where:
T_i – panel i outlet temperature as measured by the panel outlet thermocouple (^{o}C)
T_{151} – panel i inlet temperature as measured by the cooling water inlet temperature (^{o}C).
Fe_i = panel i cooling water flow rate as measured by the panel i outlet flow meter (m^3/hr).

The aspects that influence the heat loss value are shown in figure 26 below.
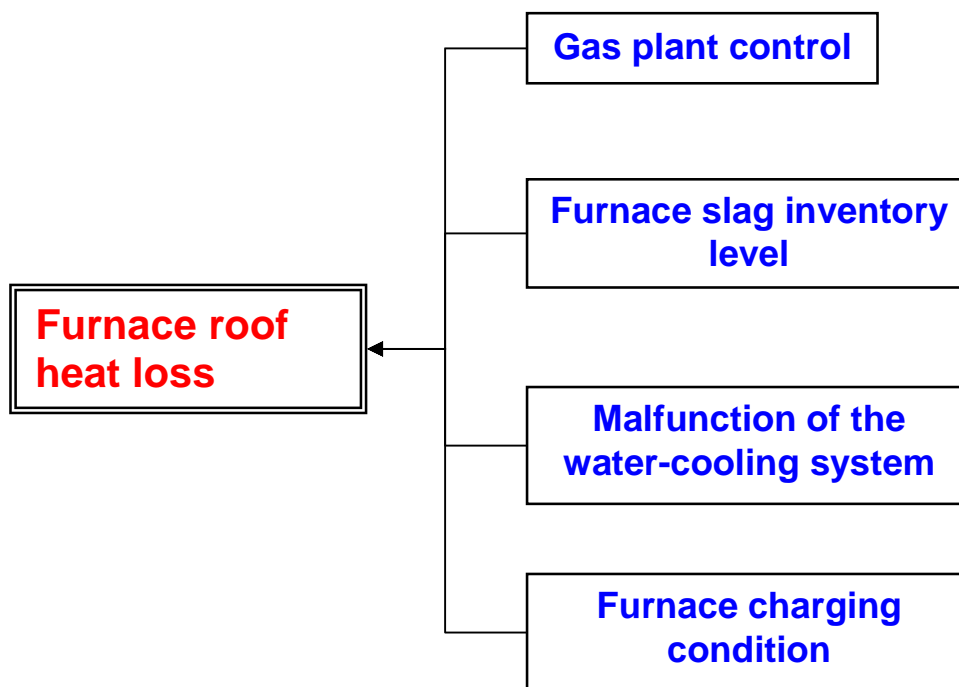
Figure 26: *The main aspects that influence the furnace roof heat loss value.*

Gas plant control: The aim of the control of the valves of the furnace gas plant is to maintain the pressure underneath the furnace roof as close as possible to neutral. If the furnace pressure is negative, it means that too much oxygen is sucked in from outside the furnace, causing combustion of CO to form CO_2 and causing the furnace roof to heat up. If insufficient suction is obtained, the hot gas and flames from the furnace interior tend to burn the rubber water cooling pipes on the outside of the roof. It is often experienced that poor control of the gas plant

results in the overall heating of the furnace cooling water and over time causes furnace trips due to high water temperatures.

Furnace slag inventory: the furnace heat loss increases when too much slag is in the furnace and therefore closer to the roof; the high slag level causes the bath to become more open and more heat is radiated towards the roof.

Malfunction of the water-cooling system: this will obviously cause the furnace water to heat up even under normal stable operation.

Furnace charging condition: it is experienced that if all of the reasons mentioned above can be eliminated, the roof heat loss is strongly affected by the charging condition. If the furnace is undercharged (empty), the heat loss value tends to be high. When the furnace is overcharged the heat loss value is low. A typical heat loss value of 6.5 MW is considered to be normal and anything significantly above or below this might reflect an over- or undercharged condition.

The stability of the furnace electrical parameters is a second way of predicting the furnace charging condition. Parameters such as resistance, power input (MW variation) and electrode movement are directly influenced by the interference of feed piles and stability of the slag bath. It is generally experienced that when the furnace becomes undercharged the parameters as mentioned above are extremely stable as shown in figure 27 below. The opposite is true when the furnace become overcharged.
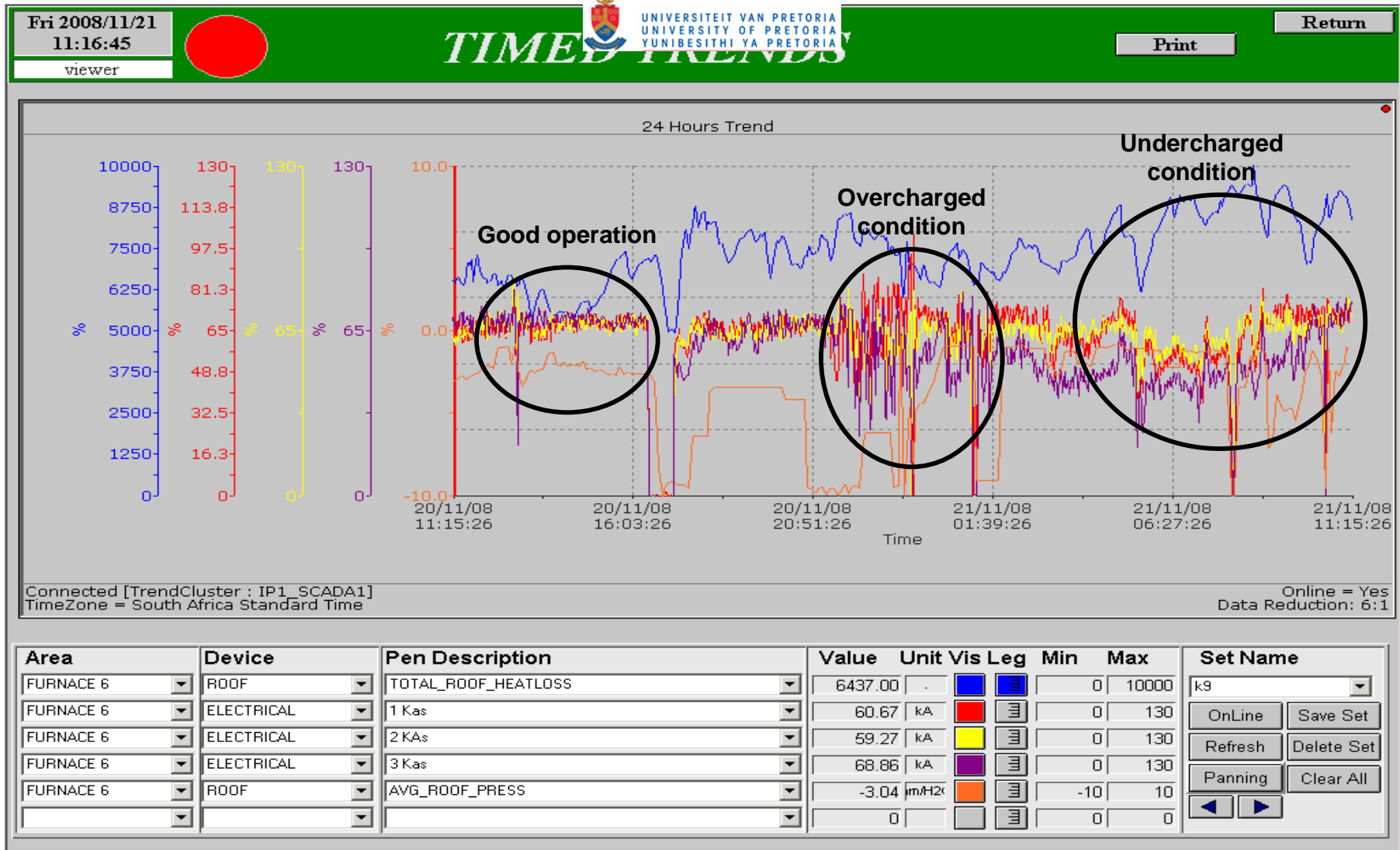
Figure 27: *The current to all three electrodes, together with heat loss and gas plant suction, illustrating that these parameters can be used to monitor furnace charging condition.*

Figure 27 is a time trend taken from live SCADA system data from furnace 6. Three distinct time periods are identified when parameters such as heat loss and electrical stability could be used to determine the charging condition. These periods are discussed below.

Good condition: the heat loss graph (blue) is stable and low. The recorded heat loss is typically between 5 MW and 7 MW. It can also be seen that the electrodes currents are stable (red, yellow and purple graphs). These show that the feedpiles are not interfering with the electrodes but are also not causing a large open bath that will relate to high heat loss values.

If the trends are followed to the right hand side, the heat loss value increases, while the electrodes stay stable. It is also seen that the gas plant over sucked the furnace (orange line), which is probably the reason for high heat loss through the roof.

Overcharged condition: the electrode currents become very unstable in this period and the heat loss decreases. This indicates a typical overcharged condition where the feedpiles are starting to interact with the electrodes and reduces the open slag bath area, which decreases the heat loss.

Undercharged condition: in this section the electrode currents are very stable as is the gas plant control. The heat loss value increases steadily which is due to the open slag bath area increasing as the furnace become undercharged.

7. Conclusions

The following conclusions are made based on the literature study, experimental work as well as practical experience in managing and optimising the open slag bath furnaces.

1) The open slag bath furnaces can be optimised in terms of power consumption, product quality, iron yield and production volumes by using a furnace control system.

2) The open slag bath furnace can be controlled with regards to both productivity and product quality by the correct application of the power/feed ratio.

3) The OSB process is extremely sensitive to the quality of the raw materials, since the feed is directly into the liquid bath and impacts directly on the energy balance. It is for this reason why an investment is recommended, to upgrade the raw material blending methods to be better suited to feed forward control.

4) The consistency of the furnace condition is determined by the consistency of decision making. It is for this reason that a central control system is proposed through the use of a mass and energy balance, which will continually balance feed rate and power input based on furnace feed mixture properties.

5) Due to the large solidification range of the slag, a high viscosity of the slag (difficult to tap) can be rectified by increasing the power/feed ratio. This will cause the slag temperature to increase and therefore reduce its viscosity.

6) Slag basicity plays an important role in controlling the slag viscosity and should be kept below 2.

7) The furnace productivity is directly proportional to its availability, since frequent stoppages negatively impact on the furnace heat balance. The availability also strongly impacts on the process control systems, since consistent furnace feed and power inputs help to reach system steady state.

8) The furnace charging condition can be monitored and controlled by using electrical, gas plant and heat loss parameters. By doing this the furnace energy balance can be controlled which will optimize furnace power consumption per ton of metal tapped.

8. Control proposal for the Open slag bath furnaces at Highveld Steel

Through this study it has become clear that a control system for the open slag bath furnaces needs to be developed in order to maximize profits from these furnaces. This section makes a few suggestions and shows the proposal in more detail.

8.1 Suggestions and important aspects

- Introduce raw material sampling to take place at least twice daily and for each kiln individually. The sampling should be done with permanently installed sampling devices.
- Upgrade the lab facility to be able to handle the increased number of samples and also to increase the accuracy of the results.
- Introduce a central computer system which links all the process inputs, outputs and disturbances.
- A dynamic mass and energy balance is required which will estimate the energy requirements of the furnace. This will standardize decision making regarding power and feed control which will lead to the furnace reaching equilibrium quicker.
- A great effort needs to be made to upgrade the data integrity and the instrumentation supporting the furnace operation. This is especially important for inputs that will be used in the mass and energy balance model.
- Dedicated personnel must be used to maintain and continually adjust the process model in order to maximize its effectiveness.

8.2 Control system design and layout

Figure 28 shows how the information from different sources around the plant can be integrated in the control system.
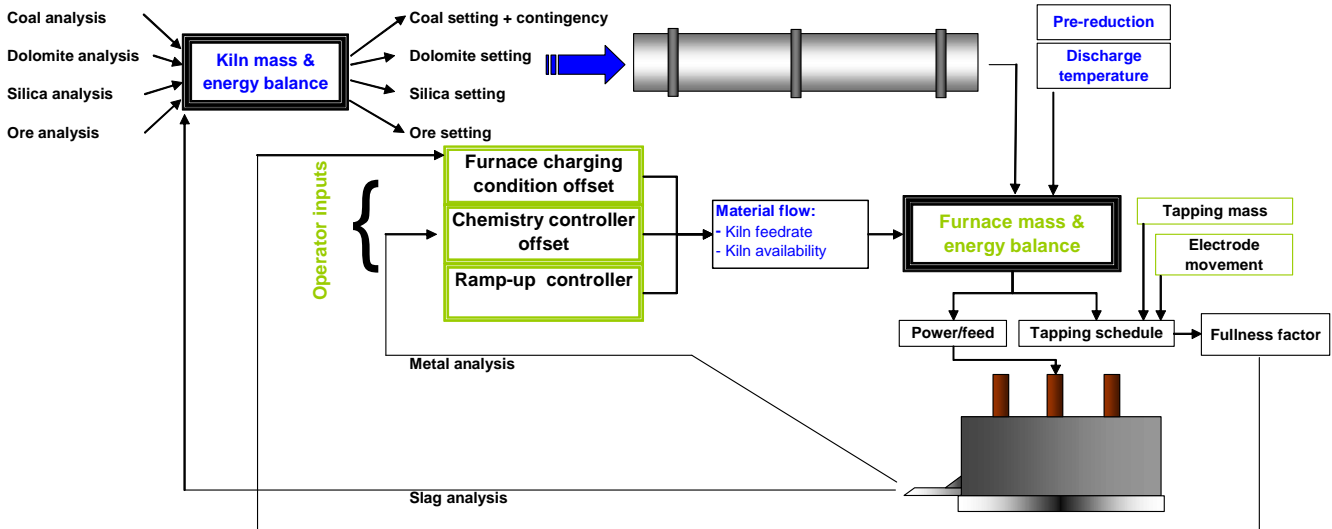
***Figure 28**: shows the proposed control strategy for the OSB furnaces*

A detailed control design is also proposed and shown in figure 29.
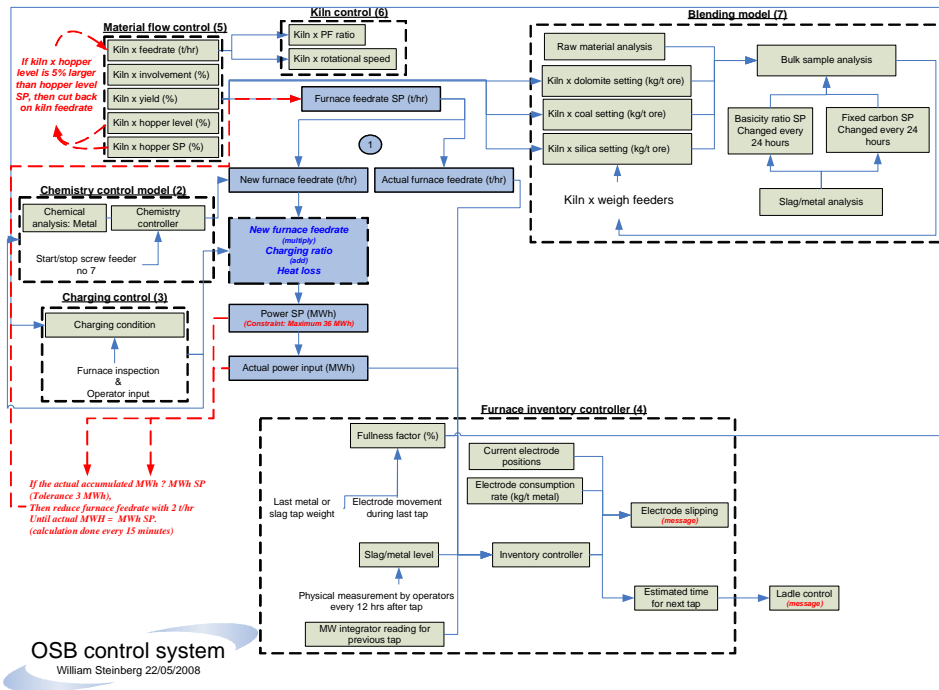
***Figure 29**: shows a detailed control system design for the open slag bath furnaces.*

9. Acknowledgements

10. Appendix

The appendix includes:

I. An operational procedure in a decision chart format, which aims to control the feed-power-ratio as well as the addition of correction material. It also helps to control the material flow between the kilns and furnaces.

II. Mass and energy balance details.

III. Furnace slag and kiln discharge chemical analysis

IV. Heat loss calculation data

V. Slag enthalpy calculation data

VI. Furnace tapping model discussion

Process control decision chart

Energy balance details

Kiln raw materials

Component	SiO2	CaO	MgO	Al2O3	Fe2O3	FeO	Fe	TiO2	V2O5	Cr2O3	Moisture	Fixed carbon	Sulphur	Ash	Volatiles	Totals		CO2	O2	N2	CO	
																	Air					
Molar mass (g/mol)	60.1	56.1	40.3	102.0	159.7	71.8	55.8	79.9	181.9	152.0		12.0	32.1					44.0	32.0	28.0	28.0	*Energies (kJ)*
Ore input (kg) 1000 25 °C																						
Composition (%)	2.35%	0.16%	1.42%	4.80%	60.00%	16.50%		12.70%	1.65%	0.32%	1%					101%						
Mass (kg)	23.5	1.6	14.2	48	600	165		127	16.5	3.2	10					1009						
kmol	0.39	0.03	0.35	0.47	3.76	2.30		1.59	0.09	0.02												
Δ H (kJ/mol)	-908300	-634900	-601600	-1675712	-823400	-265832		-944750	-1550200	-1134700												
energy (kJ)	-355249	-18115	-211955	-788863	-3093702	-610501		-1502066	-140632	-23890						-6744972	kJ					
Dolomite input (kg) 210 25 °C																						
Composition (%)	2.64%	28.80%	19.20%	0.19%	1.60%											52.4%						
Mass (kg)	5.5	60.5	40.3	0.4	3.4											110.1						
kmol	0.09	1.08	1.00	0.00	0.02																	
Δ H (kJ/mol)	-908300	-634900	-601600	-1675712	-823400																	
energy (kJ)	-83808	-684746	-601833	-6557	-17325											-1394269	kJ					
Silica input (kg) 15 25 °C																						
Composition (%)	90.20%	1.19%	2.09%	0.82%	3.66%			0.60%								98.6%						
Mass (kg)	13.5	0.2	0.3	0.1	0.5			0.1								14.8						
kmol	0.23	0.00	0.01	0.00	0.00			0.00														
Δ H (kJ/mol)	-908300	-634900	-601600	-1675712	-823400			-944750														
energy (kJ)	-204533	-2021	-4679	-2021	-2831			-1064								-217150	kJ					
Coal input (kg) 450 25 °C																						
Composition (%)	59%	5%	3%	24%	4%			5%			3%	50%	0%	16%	31%	100.0%						
Mass (kg)	42.5	3.6	2.2	17.3	2.9			3.6			13.5	225.0	1.8	72.0	137.7	450.0						
kmol	0.71	0.06	0.05	0.17	0.02			0.05				18.73	0.06									
Δ H (kJ/mol)	-908300	-634900	-601600	-1675712	-823400			-944750				0	0									
energy (kJ)	-642169	-40759	-32241	-283991	-14850			-42578				0	0			-1056587	kJ					
Kiln air input (kg) 285.7 25 °C																						**Totals**
Composition (%)																		1%	27%	72%	0%	100%
Mass (kg)																		2.9	77.1	205.7	0.0	286
kmol																		0.06	2.41	7.34	0.0	
Δ H (kJ/mol)																		-393500	0	0	-110500	
energy (kJ)																		-25542.6			0	-25542.59 kJ
																						Raw materials energy in
Total mass (kg)	74.8	58.0	50.2	57.9	534.0	145.2		115.0	14.5	2.8	23.5	198.0	1.6		137.7	1413.2		2.9	77.1	205.7	0.0	-9438520.7 kJ
Composition (%)	5.3%	4.1%	3.5%	4.1%	37.8%	10.3%		8.1%	1.0%	0.2%	1.7%	14.0%	0.1%		9.7%	100.0%		1%	27%	72%	0%	-2621.8 kW
energy (kJ)	-1285758.6	-745640.2	-850708.3	-1081432.1	-3128706.7	-610501.3		-1545709.0	-140632.1	-23889.9			0.0			-9412978.2 kJ		-25542.6	0.0	0.0	0.0	-25542.6 kJ
																						-2.6 MW

Carbon combusted	14%		
Pre-reduction (%)	40%	17%	*Metallisation*
Kiln spillages (%)	12%		
Moisture yield (%)	0%	0	kg
Volatiles yield (%)	0%	0	kg
Ash yield (%)	65%	0.00	kg

Energy balance details

Furnace inputs

Component	SiO2	CaO	MgO	Al2O3	Fe2O3	FeO	Fe	TiO2	V2O5	Cr2O3	Moisture	Fixed carbon	Sulphur	Ash	Volatiles	Totals		CO2	O2	N2	CO	
Molar mass (g/mol)	0.0	31.0	173.0	-516.0	337.9	168.9	168.9	0.0	0.0	-290.0		(244)	0.0					-244.0	0.0	0.0	-244.0	**Energies (kJ)**
Kiln discharge (kg)	1109	550 °C																				
Composition (%)	6.3%	5.8%	5.1%	5.4%		46.8%	7.4%	11.7%	1.5%	0.3%		9.5%	0.1%			100.0%						
Mass (kg)	70.2	64.6	56.2	59.8		519.5	82.5	129.4	16.5	3.2		105.7	1.6			1109.2						
kmol	1.2	1.2	1.4	0.6		7.23	1.48	1.6	0.1	0.0		11.7	0.0									
Δ H (kJ/mol)	-876563	-609017	-577298	-1619521		-237415	16449	-909123	-1468631	-1072674		8123	19441									
energy (kJ)	-1023927	-701559	-805516	-949105		-1716835	24298	-1473080	-133232	-22584		94751	960			-6705828 kJ						

																		1%	27%	72%	Totals 100%
Fce air ingress (kg)	0.0	25 °C																1%	27%	72%	100%
Composition (%)																		0.0	0.0	0.0	0.0
Mass (kg)																		0.0	0.0	0.0	
kmol																		-369494	16602	16211	
Δ H (kJ/mol)																		0	0	0	0 kJ
energy (kJ)																					

Kiln discharge energy out: -6705827.8 kJ ; -1862.7 kW ; -1.9 MW

Correction material (kg)	0.0	25 °C														
Composition (%)	2.35%	0.16%	1.42%	4.80%	68.00%	5.00%		11.80%	1.54%	0.32%	5%					100%
Mass (kg)	0	0	0	0	0	0		0	0	0	0					0
kmol	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00						
Δ H (kJ/mol)	-908300	-634900	-601600	-1675712	-823400	-265832		-944750	-1550200	-1134700						
energy (kJ)	0	0	0	0	0	0		0	0	0						0 kJ

Kiln energy requirement: 2732693.0 kJ ; 759.1 kW ; **0.76** MW

Partitioning factors	To metal	To slag	To dust	To gas	Sum
Fe	93.0%	5.0%	2%		100.0%
Si	3.0%	92%	5%		100.0%
Ti	1.7%	98%	0%		100.0%
V	78.6%	20%	1%		100.0%
Cr	72.9%	26%	1%		100.0%
C	17.3%	0%	2%	88%	107.5%
S	11.0%	89%	0%		100.0%
Ca	0.0%	100%	0%		100.0%
Mg	0.0%	100%	0%		100.0%
Al	0.0%	100%	0%		100.0%

Furnace outputs

Slag produced (kg)	421.1	1460 °C														
Composition (%)	15.3%	15.3%	13.4%	14.2%		7.4%	2.8%	30.2%	0.8%	0.2%			0.3%			100%
Mass (kg)	64.6	64.6	56.2	59.8		31.28	11.8	127.23	3.37	0.84			1.4			421
kmol	1.075	1.152	1.395	0.586		0.435	0.211	1.593	0.019	0.005			0.044			
Δ H (kJ/mol)																
energy (kJ)																-4454995 kJ

Dust produced (kg)	18.3	1300 °C														
Composition (%)	19%	0%	0%	0%		68%		0%	1%	0%		12%				
Mass (kg)	3.5093	0	0	0		0.17		0	0.165	0.032		2.1				
kmol	0.058405786	0	0	0		0.17		0	0.00090719	0.00021054		0.2				
Δ H (kJ/mol)	-813660	-567938	-538131	-1523454		-191960		-852480	-1325891	-975787		23789				
energy (kJ)	-47522.46919	0	0	0		-33434		0	-1202.83033	-205.441733		4185				-78179 kJ

Component	Si				Fe	Ti	V	Cr	C	S			
Molar mass (g/mol)	28.1				55.8	47.9	50.9	52.0	12.0	32.1			
Metal produced (kg)	470.9	1360 °C											
Composition (%)	0.2%				93.7%	0.28%	1.54%	0.34%	3.88%	0.037%			100%
Mass (kg)	0.98				441.34	1.30	7.26	1.60	18.28	0.01			
kmol	0.04				7.90	0.03	0.14	0.03	1.52	0.01			
Δ H (kJ/mol)	83886				64682	59578	59414	66967	26401	45081			
energy (kJ)	2940				511158	1622	8473	2056	40177	245			566671 kJ

Furnace products energy out: -4585462.6 kJ ; -1273.7 kW ; -1.3 MW

								0%	0%	0%	100%	Totals 100%
Gas production (kg)	217.3	1000 °C						0%	0%	0%	100%	100%
Composition (%)								0.0	0.0	0.0	217.3	217.3
Mass (kg)								0.00	0.00	0.00	7.76	7.8
kmol								-345735	31983	30996	-79778	
Δ H (kJ/mol)								0	0	0	-618959.1169	-618959.1 kJ
energy (kJ)												

Furnace energy requirement: 2120365.1 kJ ; 589.0 kW ; **0.589** MW

Slag and kiln discharge lab analysis

ANALYTICAL REPORT: Slag and Coal samples

To:	**Marcus Erwee**	Date of Request	6/5/2008	From :	UIS Analytical Services
	University of Pretoria				Analytical Chemistry
					Laboratories 4, 6
Tel:	0726021869				Tel: (012) 665 4291
					Fax: (012) 665 4294
Fax:					

Certificate of analysis: 4514

Note: all results in percentage (%) unless specified otherwise

Sample Origin	Sample ID	Fe(tot)	Fe⁰	FeO	Fe$_2$O$_3$	C	H	N
		%	%	%	%	%	%	%
4514-01	**Furnace 5 Slag 19/4/2008**	8.80	3.56	6.71	0.03			
4514-02	**FCC 6 Slag 19/4/200**	9.77	1.07	11.2	0.01			
4514-01QC	**Furnace 5 Slag 19/4/2008**	8.81	3.61	6.68	0.01			
4514-03	**Sample 1 Grof HLS Coal Floats 2,0**					59.8	<0.01	0.777
4514-04	**Sample 1 Fyn HLS Coal -710 um**					17.9	<0.01	0.165
4514-05	**Sample 2 Grof HLS Coal Floats 2,0**					61.9	<0.01	0.685
4514-06	**Sample 2 Fyn HLS Coal -710 um**					16.6	<0.01	0.159
4514-07	**Sample 3 Grof HLS Coal Floats 2,0**					15.2	<0.01	0.17
4514-08	**Sample 3 Fyn HLS Coal -710 um**					11.7	<0.01	0.137
4514-09	**Sample 4 Grof HLS Coal Floats 2,0**					66.1	<0.01	0.953
4514-10	**Sample 4 Fyn HLS Coal -710 um**					66.2	0.09	0.876
4514-07QC	**Sample 3 Grof HLS Coal Floats 2,0**					15.4	<0.01	0.157

Comments / additional information: Please note that where no results are filled in, the Minimum as in the row below the element will apply

	Identification of test methods:		Chemical elements:	
			Instrument:	
			Documentation:	

Date:	6/13/2008	Date:	6/17/2008	
Analysed by:	RUTH	Authorised : J Oberholzer		Page 1 of 1

Furnace shell thermocouple position
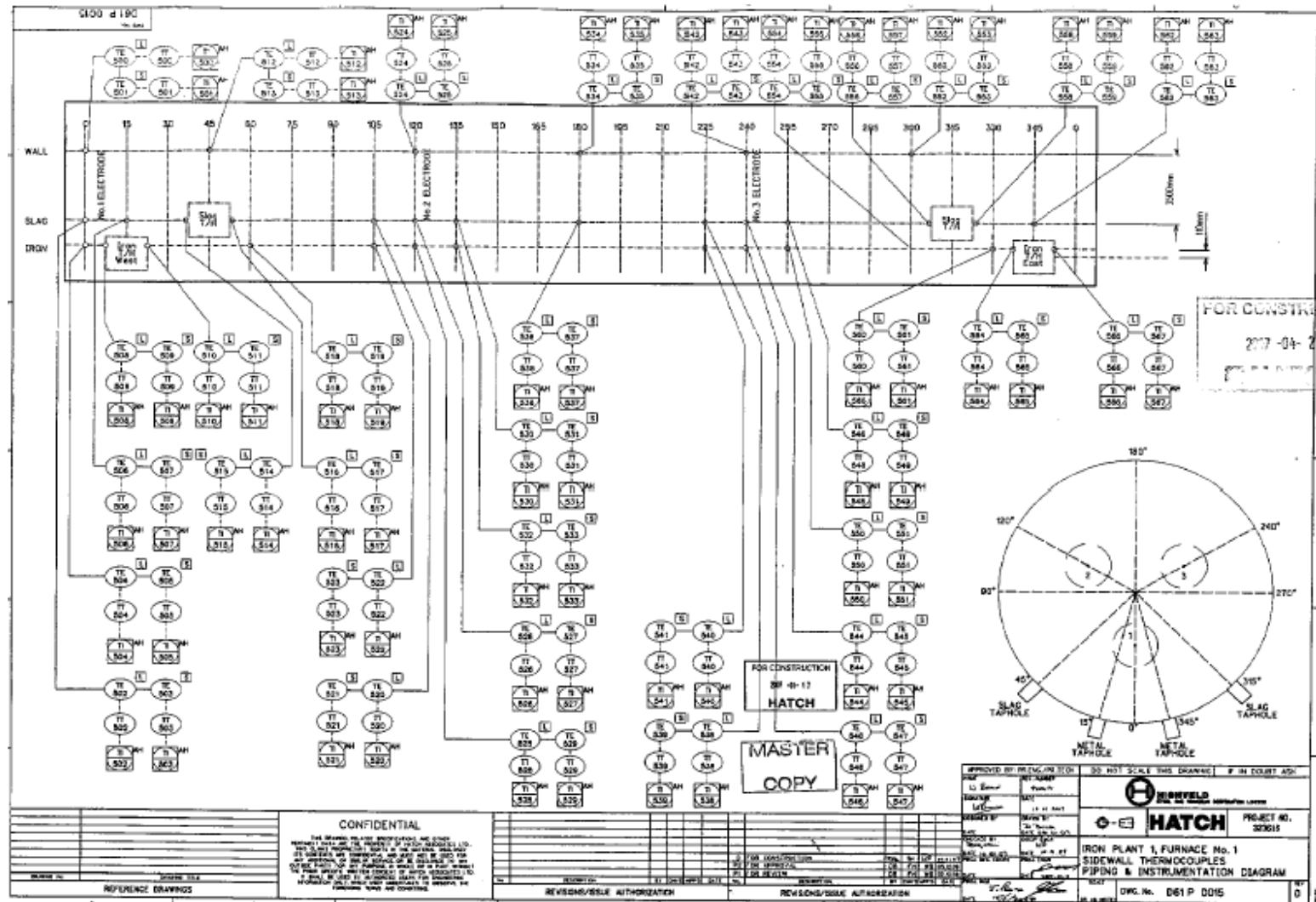
Slag enthalpy calculation data

Basic composition (from mass balance):	
Element	Calculated analysis
S	0.4%
SiO_2	16.5%
CaO	16.6%
MgO	14.0%
Al_2O_3	13.6%
FeO	6.9%
V_2O_5	0.7%
TiO_2	28.2%
Cr_2O_3	0.2%

Normalised slag compositions used in calculations			
Fraction of Ti as Ti_2O_3:	0	0.3	0.5

%SiO_2	17.12	17.27	17.37
%CaO	17.22	17.37	17.48
%MgO	14.52	14.65	14.73
%Al_2O_3	14.08	14.20	14.29
%FeO	7.19	7.25	7.29
%V_2O_3	*Added to Ti_2O_3*		
%Ti_2O_3	0.61	8.59	13.98
%TiO_2	29.27	20.67	14.85

Enthalpies from FactSage model:			
T (K)	H (J/kg)	H (J/kg)	H (J/kg)
1673	-11398800	-11292600	-11225400
1773	-11266600	-11161800	-11095300

Enthalpy of SiO2-CaO-MgO-Al2O3-FeO portion

%SiO_2	24.41
%CaO	24.56
%MgO	20.70
%Al_2O_3	20.08
%FeO	10.25

T (K)	H (J/kg)	*(from slag enthalpy model)*
1763	-11106006	
1773	-11093690	

Furnace tapping model discussion

Currently the furnace is tapped for both metal and slag based on the energy input between consecutive taps. Slag tapping occurs after every 100 MWh from the last slag tap, while metal is tapped after 120 MWh. For large enough taps to be made the furnace must be at sufficiently high temperatures in order to ensure low viscosity of the metal or slag. The furnace must also contain a sufficiently large inventory which provides the pressure to give sufficient slag and metal flow rates. The mass balance can be used to predict the amount of metal or slag that was melted and tapping must therefore be scheduled whenever one full kling ladle or slag pot can be filled. The mass balance is used to determine the duration between the taps. By using the mass and energy balance it will be ensured that the correct power/feed ratio is maintained while correctly scheduling the metal/slag taps. Table A1 shows what the correct time span between each metal tap should be, in order to melt and accumulate a tap weight of 80 tons, as a function of average power input per hour. It is calculated that each MW adds approximately 0.52 tons of metal to the furnace inventory.

Table A1: shows the duration between metal taps as a function of average furnace power input.

Power input (MW)	Time between taps (hrs)
20	9
25	7
30	5
35	4

It is often encountered that the tapping of metal and slag cannot only be done based on MWh or mass accumulation principles. The electrode position often forces one to tap the furnace, since as the furnace inventory increases the electrodes move upwards until the entire stroke is used. If the electrodes reach their upper limit the effective power input will be reduced for safety reasons. At this point the furnace needs to be tapped to get the inventory level down again. However, the furnace charging condition influences the effective furnace volume: large banks are present during an overcharged condition and smaller ones when the furnace is empty or undercharged.
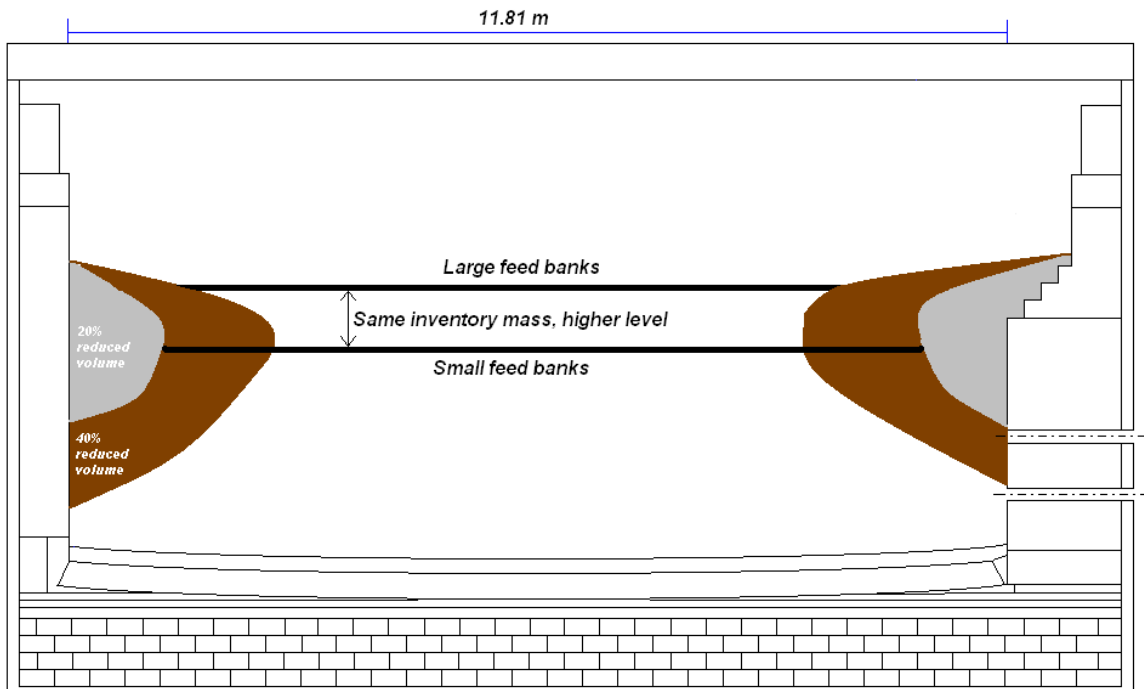
Figure A1: *Schematic illustration of how the furnace charging condition affects the furnace inventory level.*

Figure A1 shows that the same slag and metal mass inside the furnace could result in different heights based on the charging condition of the furnace. The mass and energy balance can therefore be used to schedule taps successfully only if the furnace charging condition is known. If not, the mass and energy balance might say that the furnace can be tapped after 4 hours, while in actual fact the slag height is already causing reduced power input due to the electrode position.

Based on volume calculations a furnace "filling" value can therefore be calculated by comparing the actual amount of metal or slag tapped with the volume change that was experienced in the furnace. The value will then be able to relate to the effective charging condition of the furnace. This information can be used to alter the furnace charging condition in order to ultimately establish a constant furnace inventory level.

Table A2 shows the expected slag and metal mass as a function of the mixture feed rate into the furnace. This is calculated based on a tapping model developed for the furnace.

Table A2: *shows the expected tappable slag and metal mass as a function of mixture feed rate*

Avg MW (over 24 hrs)	Iron mass (t)	Slag mass (t)
20	255	201
25	318	250
30	382	300
36	459	360
40	510	402

The tapping model is based on the concept of a fullness factor as described above and uses the mass balance to determine the split between slag forming elements and metal contributors. Table A3 shows the variables that were used in the model.

Table A3: *shows the variables used in the tapping model*

Model variables	
ρ_m	6.94
ρ_s	2.2
Electrode stroke (m)	1
Furnace diameter (m)	12.14
kWh/ton mixture	800
% Iron in mixture	42.5
% Slag in mixture	33.9
Furnace inside height (m)	4.74
Slag taphole measured from bottom (m)	1.36
Iron taphole measured from bottom (m)	0.8
Roof thickness (m)	0.3

The actual Excel tapping model is included on a CD containing also the mass and energy balance.

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