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Ilmenite Smelting at Ticor SA

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Abstract – Ticor SA began with a detailed feasibility study in 1995. The Hillendale mine (situated between Richards Bay and Empangeni) and Mineral Separation Plant were approved in 2000. The smelter, just outside Empangeni, consists of two 36 MW DC arc furnaces that were commissioned in 2003. Experiences gained during the initial commissioning of the furnaces proved valuable in later commissioning work, as shown by the increase in ramp-up rates. The capacity of the plant is 250 kt/a TiO_2 slag and 145 kt/a of pig iron.

THE HEAVY MINERALS INDUSTRY

Mineral Sands is a term used to refer to deposits of heavy minerals such as ilmenite, zircon, rutile, leucoxene, and monazite. These sands originate from igneous rocks, such as granite and basalt, which have weathered to release the heavy minerals. Mineral Sands deposits are usually found in strands along old coastal regions where weathering and erosion have separated the heavier minerals from the lighter minerals and have formed concentrated ore bodies.

Australia, South Africa, the USA, Canada, and India are the principal producers of mineral sands. The Richards Bay reserves in South Africa are among the largest in the world.

Mineral Sands are used as a source of titanium minerals. The most important naturally occurring titanium minerals are ilmenite, rutile, and leucoxene. These minerals are mined to produce titanium dioxide (TiO_2) feedstock for pigment manufacturers. The minerals are used as feedstock either in their natural form or in an upgraded form, such as synthetic rutile and titania slag, which are produced through the secondary processing of ilmenite.

TiO_2 feedstock is predominantly used to produce pigments, titanium metal, welding fluxes, and other specialised products. About 95% of titanium dioxide feedstocks are used in the production of titanium dioxide pigments, which are widely used in paints, paper, and plastics. TiO_2 pigment is extremely refractive, and adds brightness, whiteness, and opacity to products. Because of its unique 'hiding power' and non-toxicity, it is a major ingredient in the manufacturing of paint, plastic, papers, and inks. It is also widely used in food products, sunscreens, and other cosmetics.

The three South African based producers of TiO_2 feedstock – Richards Bay Minerals, Namakwa Sands, and Ticor South Africa (Ticor SA), all produce TiO_2 slag via the smelting of ilmenite. The whole industry – from mining of heavy mineral deposits through to pigment manufacturing – is highly competitive, with little sharing of metallurgical process or marketing information between companies.

THE ORIGIN OF TICOR SA

In 1995, Iscor Mining (now Kumba Resources) initiated the detailed feasibility study for the IHM Heavy Minerals Project. The feasibility study formed the basis for a detailed engineering and design phase, which commenced in November 1996. This continued into 2000, when the Iscor Board approved the implementation of Phase 1 of the Project – Hillendale mine and the Mineral Separation Plant. Construction of the Smelters – Phase 2 – was subsequently announced on 15 August 2001.

[During February 2001, Ticor Ltd, an Australian publicly listed company, acquired 40% of the IHM Heavy Minerals Project, together with management control. Hence the change of name to Ticor South Africa. By 2005, the TiO_2 feedstock production under Ticor's management control was over 11% of the world's feedstock production, thereby establishing Ticor as one of the industry leaders. During October 2005, minority shareholders in Ticor Ltd accepted a proposal from Kumba Resources Ltd, to re-acquire shares in, and management control of, Ticor (by implication also of Ticor SA). Finalisation of this transaction is being pursued at the time of writing this document.]

Hillendale mine and the Central Processing Complex (CPC) are located in northern KwaZulu Natal, with the mine positioned roughly between Richards Bay and Empangeni, and the CPC just outside Empangeni, as shown in Figure 1. The CPC contains both the Mineral Separation Plant and Smelters.

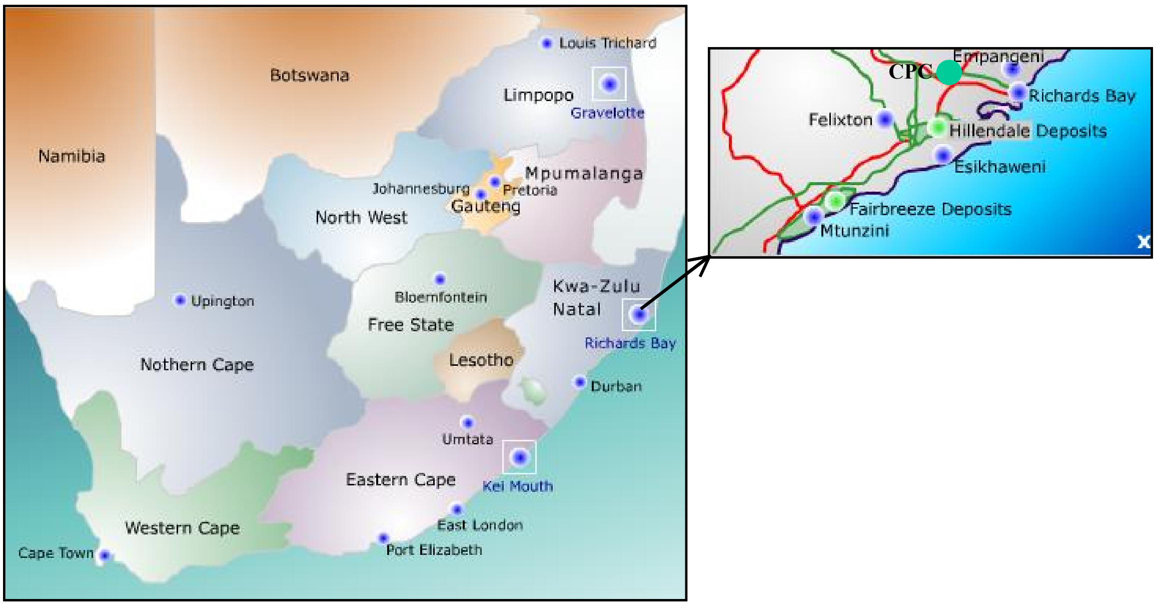

Figure 1: Physical location of the Hillendale mine and CPC

Commissioning of the Hillendale mine and the Mineral Separation Plant was completed in 2001, producing ilmenite, zircon, and rutile at design capacity. The commissioning of Furnace 1 commenced in March 2003, followed by that of Furnace 2 in October of the same year. The downstream Metal Treatment and Slag Processing Plants were also commissioned during 2003. Furnace 2 was commissioned for its second campaign during January 2005.

The products from Ticor SA and their nameplate capacities are shown in Table 1.

Table I: Nameplate capacity of the final products from Ticor SA

Product	Nameplate capacity, kilo tons per annum
TiO_2 slag	250
LMPI (low Mn pig iron)	145
Ilmenite	550
Zircon	60
Rutile	30

Ticor South Africa's vision is to be the benchmark in the heavy minerals industry. The strategic focus is on sustainability, international competitiveness, optimization of current operations, and proactively seeking value-adding initiatives to improve the business.

DEVELOPMENT OF ILMENITE SMELTING AT TICOR SA

Between 1995 and 2001, Ticor SA (then IHM Heavy Minerals) conducted twelve ilmenite-smelting campaigns on the 3 MVA pilot furnace at Kumba Resources' Research and Development facilities. These campaigns varied in length from one week to six weeks, with the majority being of the order of two weeks. The objectives of these campaigns included the following:

- Testing of different feedstocks for ilmenite smelting. This included various ilmenite and reductant sources.
- Evaluating the feasibility of water granulation of slag
- Understanding the key operating parameters of ilmenite smelting, such as the importance of an accurate feed system
- Development of a suitable operating philosophy
- Investigating the cooling behaviour of TiO_2 slags
- Producing slag marketing samples
- Defining the specifications of a suitable information system
- Training of operational and metallurgical personnel

These campaigns laid the foundations for the pyrometallurgical knowledge and skills of Ticor SA on ilmenite smelting. The experience gained during these campaigns was priceless when specifications were laid down during the design phase of the plant, and during commissioning of the industrial-scale furnaces. With these campaigns, and the leadership behind them, a culture of understanding the origin and mechanism of a problem prior to developing solutions was established.

THE ILMENITE SMELTING PROCESS

Raw material preparations for the smelting process are done within the Mineral Preparation Plant, which, amongst others, contains the URIC (Unroasted Ilmenite Circuit) and the Reductant Preparation Plant. In the former, crude ilmenite from the separation plant is upgraded via magnetic separation technology before being fed into the furnaces. The as-received anthracite, in turn, is dried, and the fines removed before smelting.

Ilmenite is continuously fed, together with anthracite in a tightly controlled ratio, through the hollow electrode into the operating furnace. The reduction reaction can be written as follows (reaction is not balanced):

$$FeTiO_3\ (s) + C\ (s) \rightarrow M_3O_5\ (l) + Fe\ (l) + CO\ (g) \quad \text{where M = Ti, Fe} \qquad [1]$$

The slag (written as M_3O_5) contains titanium in both the +3 and +4 oxidation states. The resultant slag has a lower density than the iron, and separation of the two liquid products occurs within the furnace.

The primary product - titanium oxide slag - contains an average of 85% TiO_2. (Total Ti is expressed as TiO_2, as Ti in the slag is present in both the +3 and +4 oxidation states.) In addition, the slag also contains approximately 10% FeO. Also present are impurities such as SiO_2, Al_2O_3, MgO, MnO, CaO, Cr_2O_3, V_2O_5, and ZrO_2. Due to the reducing conditions in ilmenite smelting, some of the impurities (such as MnO) are partially reduced, and report also to the metal phase. The maximum limits for impurities in both the slag and iron are fixed by contractual agreements between supplier and customer.

The smelting and reduction processes are conducted within a crucible of solidified, high titanium content slag (known as the freeze lining), contained within the furnace refractory walls. This freeze lining protects the magnesia refractory from chemical slag attack. Apart from increasing the MgO content of the slag, and thereby exceeding the maximum impurity specification, chemical attack by the slag on the magnesia bricks reduces the life of the refractory lining. A worst-case scenario would be chemical erosion through the thickness of the lining, leading to a side-wall breakthrough. Protecting the integrity of the freeze lining, through firm control over the mass and energy balance within the process, is therefore one of the primary objectives of ilmenite smelting.

Slag and iron are tapped periodically from separate sets of tapholes located around the circumference of the furnace. The slag tapholes are on a higher elevation than those for iron. Slag is tapped into 20 t steel pots, and cooled for several hours within these pots before the slag blocks are tipped out. These blocks are subsequently transported to the blockyard where they are cooled under water sprays for a number of days. They are then crushed, milled, and separated according to size fractions, as required by the pigment manufacturers.

The tapped pig iron is re-carburised and desulphurised, and cast into 7 kg pigs for use in (among others) the automotive industry.

COMMISSIONING OF THE TWO DC ILMENITE SMELTING FURNACES

A simplified cross-section of one of the 36 MW (50 MVA) DC furnaces is shown in Figure 2. The Demag-designed furnace has a circumference lined, for the most part, with MgO refractory bricks. The electrical circuit supports a single hollow graphite electrode, combined with four billet anodes built into the hearth. Each anode consists of a copper water-cooled base, joined, through resistance welding, to a steel upper part reaching up into the working lining of the refractory hearth. The UCAR-designed roof is spray cooled, and isolated from the current-carrying electrode by a refractory centrepiece.

The commissioning of Furnace 1 started during March 2003, followed by that of Furnace 2's first campaign in October 2003. This first campaign of Furnace 2 was ended during August 2004 to implement design changes. Commissioning of Furnace 2's second campaign commenced in January 2005.

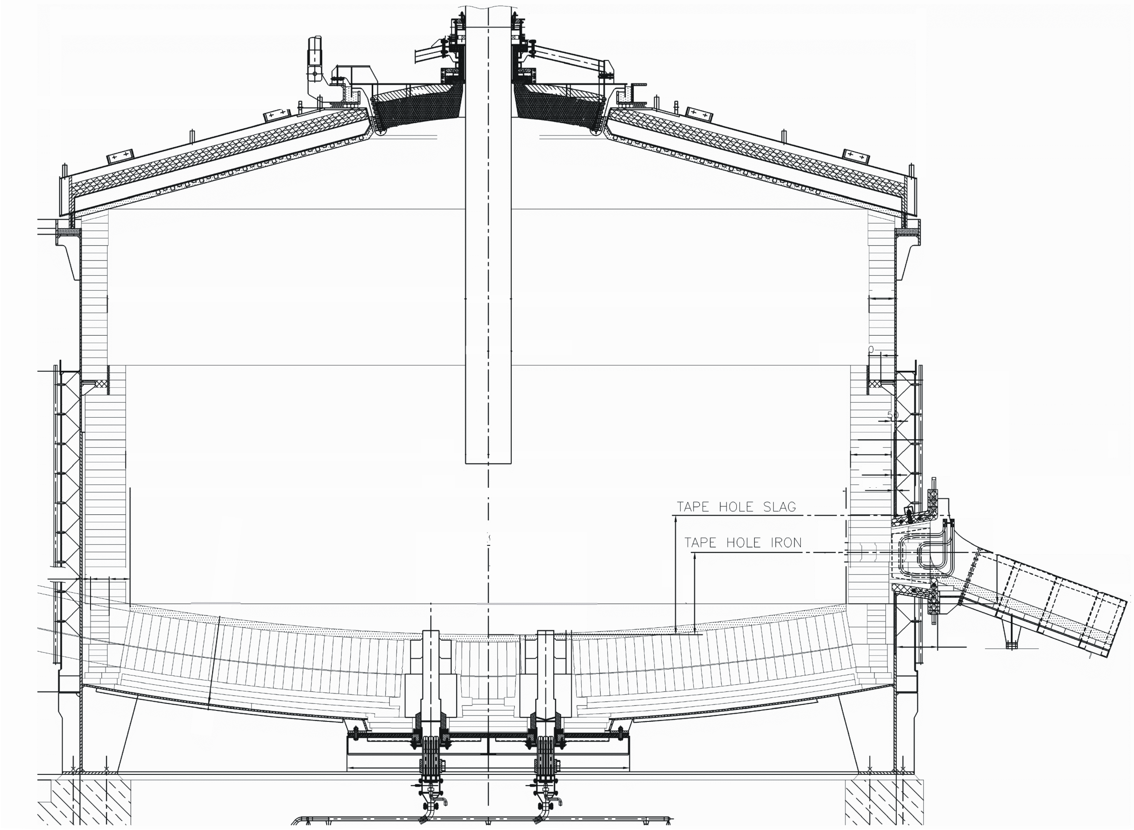

Figure 2: Cross section of the Ticor SA DC ilmenite-smelting furnace

For each of the three commissioning instances, the hot commissioning activities were grouped into six phases. Each of these phases followed on from each other, with the start of the next phase dependent on the successful completion of the previous phase. For each phase, the desired outcomes were set as criteria for completion, and agreed to by the various parties. A list of activities required to reach these criteria was subsequently defined and executed.

1. Preparations, including measuring the final internal dimensions of the furnace, and loading the initial burden consisting of scrap metal and/or metal pigs.
2. Preheating the refractory lining with hot gas.
3. Initial melting of the burden with the electrical arc.
4. Commencing feed, and filling the furnace with ilmenite and anthracite up to the taphole levels.
5. Tapping the first slag and iron, and hot commissioning of the tap-floor equipment.
6. Stabilising the process, and ramping-up feed rates and production activities.

Many of the initial criteria were based on experience from the pilot plant campaigns at the Kumba Research facilities. As per the nature of commissioning, new challenges presented more learning opportunities, which were worked into the criteria of subsequent commissioning programmes. Some of these interesting learning opportunities are described below.

Gas preheating of the refractory lining

To enable gas preheating, several burners were positioned through the furnace roof, and fired with Sasol gas and air. The gas volume and air ratio were controlled using thermocouples installed through the roof, protruding downwards into the furnace freeboard. The Sasol gas used was methane rich, yielding the following combustion reaction:

$$CH_4\ (g) + O_2\ (g) = CO_2\ (g) + 2\ H_2O\ (g) \quad [2]$$

Hence, when water dripping from the off-gas duct of Furnace 1 was detected during the Furnace 1 refractory preheat of December 2002, it was initially thought that the cause was water originating from the combustion of Sasol gas. However, on further investigation, the volume of water originating from this source proved too little to be the sole source. Incorporating the high air volumes used, the high humidity, and ambient temperatures during December months in KwaZulu Natal into the combustion environment, pointed to the source of the water: as the gas volumes are increased to reach higher preheating temperatures, the water volume blown as vapour into the furnace increased, while the internal furnace pressure increased. As these gases were condensed and cooled when passing out of the furnace into the off-gas duct, conditions favoured condensation of water onto the water-cooled off-gas duct. This water flowed directly back into the furnace, damaging sidewall and hearth refractories.

The hydration damage to the magnesia bricks was extensive, and necessitated a complete refractory rebuild of Furnace 1. During the subsequent commissioning periods of Furnace 1, and both commissioning campaigns of Furnace 2, the following control actions were implemented:

- A temporary exhaust duct was installed on an inspection hole in the roof, and used to vent combustion gas during the initial hours of preheating. Following a short upward portion, this duct was directed downwards, preventing any condensation from flowing back into the furnace. During this period the off-gas duct was blanked off at the upper end.
- Water volumes used for cooling of the off-gas duct were limited to control the water temperatures to just below maximum design temperatures, while water temperatures were manually kept high by switching off cooling towers in the water-plant. The lower limits for these temperatures were calculated from the preheating temperature as measured from freeboard thermocouples, the relative humidity, and ambient temperature, as shown in Figure 3.

Following these measures allowed for successful preheating of Furnace 1 during the following year in February, as well as the two subsequent commissioning instances of Furnace 2.

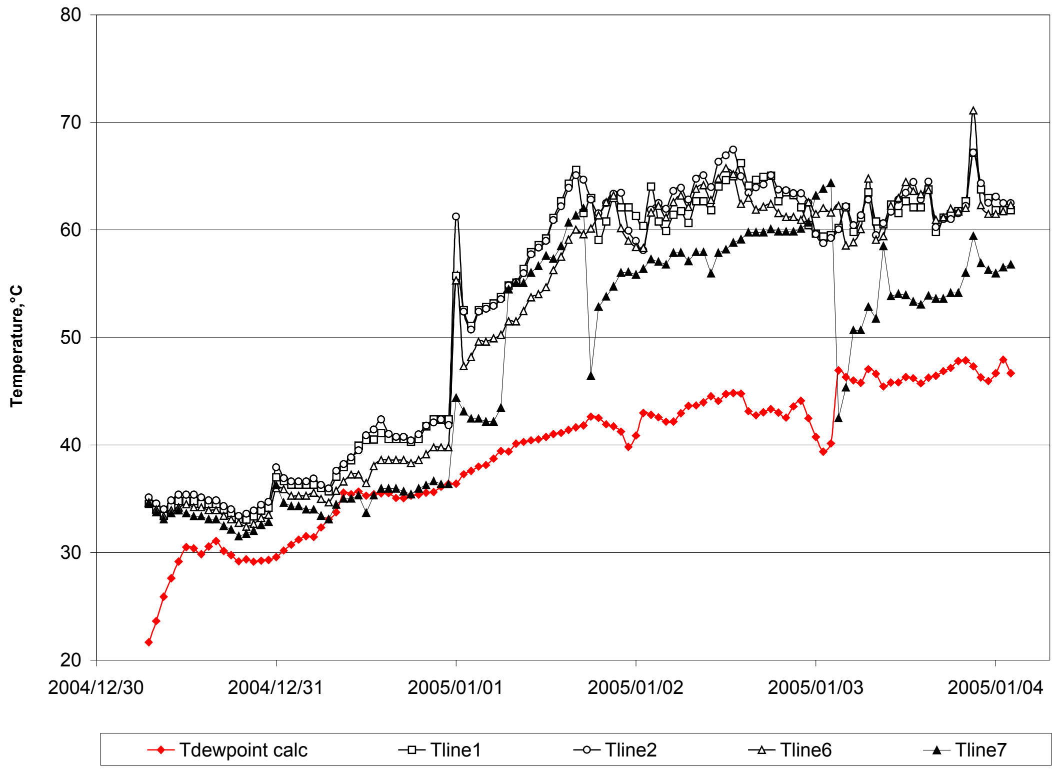

Figure 3: Actual off-gas duct water temperatures. By allowing the cooling-water temperatures to increase, these temperatures were controlled to remain above that of the calculated condensation temperatures.

Expansion of the hearth refractories

Magnesia refractory, pre-fired at temperatures equal to its operation conditions, has a linear and reversible expansion profile.[1] During preheating of the refractory lining (step 2 of the commissioning programme), a primary criterion was to ensure sufficient expansion of the refractory bricks to prevent penetration of liquid iron into the hearth.

During installation of a refractory lining, an allowance is provided for expansion, by building in expansion inserts of specified thickness at calculated intervals. The number and spacing of these expansion inserts are determined from two opposing forces: (i) the yield strength of the furnace shell, and (ii) the temperature at which the expanded bricks will take up the total expansion allowance. Refractory expansion, additional to that which is allowed for with inserts, exerts forces on the steel shell. To ensure mechanical integrity of the shell, these forces must be within the safety margins of the steel's yield strength. This constraint increases the design allowance for expansion inserts, which increases the critical temperature at which joints between bricks will close up fully. Reaching this 'critical temperature' during the preheating stage proved to be a challenge with each commissioning instance.

While the freeboard thermocouples were used to control preheating rates, the temporary thermocouples installed between the sacrificial lining and the hot-face surface of the hearth were monitored to infer the expansion of the hearth.

Heat-up rates and holding periods were followed, as prescribed by the furnace and refractory designers and manufacturers. Towards the end of the preheating period, the gas air supply system, combined with the volume capacity of the furnace off-gas system, constrained the energy input into the furnace. In addition, transfer of energy in the freeboard through the sacrificial layer into the hearth's working lining was difficult. Although the primary root cause for the iron penetration (shown in Figure 4) found during the refractory breakout following Furnace 2's first campaign, was identified as a design deficiency in the hearth steel structure, several ideas to improve the heat transfer into the working lining were nonetheless implemented. These included:

- Changing the sacrificial lining to a material with a higher thermal conductivity.
- Decreasing the volume of the initial burden, and even suspending the burden in the area directly above the centre hearth. This allowed improved gas circulation.
- Installing continuous expansion measurement to replace the manual measurements, thereby decreasing measurement errors.
- Installing an increased number of permanent double thermocouples in the hearth, with the deep thermocouple positioned between the hot and cold face, instead of the previous configuration where single thermocouples were positioned below the cold face. This allowed energy flux calculations to be used to calculate the temperature on the hot face surface.
- Extending the holding period at the maximum preheating temperature from 1 or 2 days, to up to 14 days.

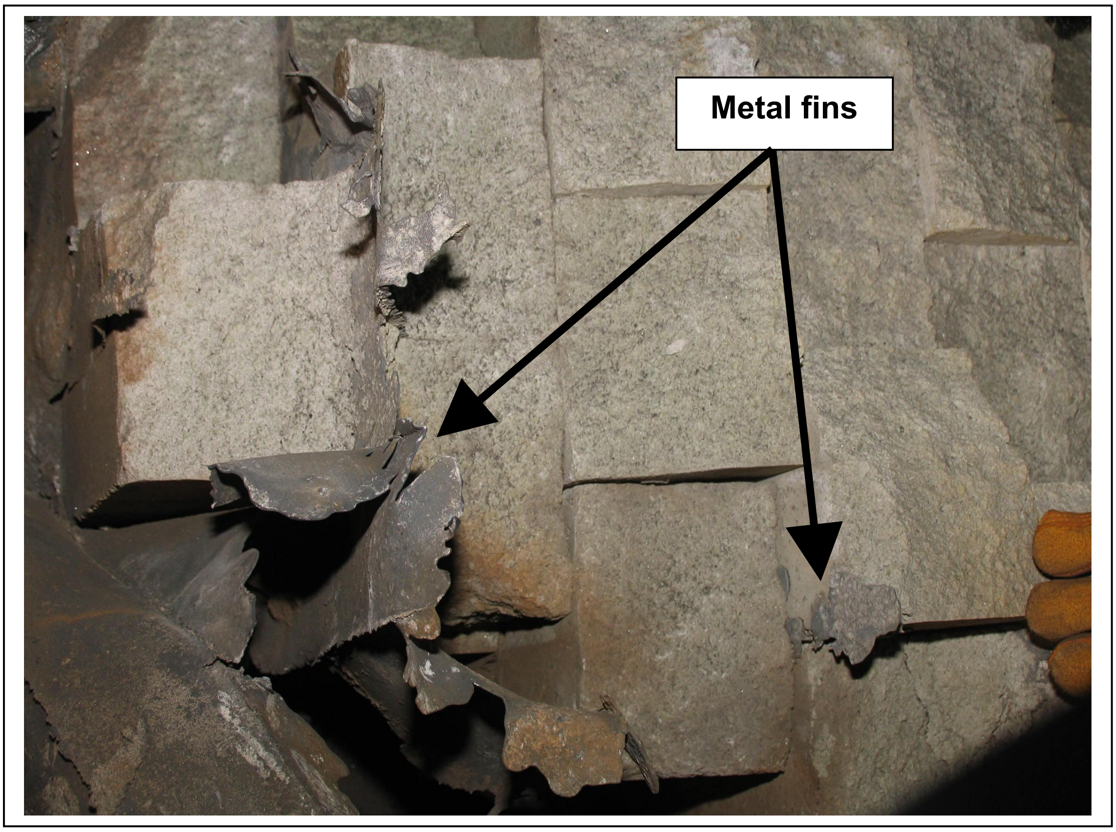

Figure 4: Iron penetration into the hearth found after the refractory break-out of Furnace 2

Understanding anode behaviour

Up to the early 1990s, existing ilmenite-smelting furnaces were six-in-line, rectangular, AC furnace configurations. Namakwa Sands was the first to use circular DC arc furnaces for ilmenite smelting. The commissioning of Ticor SA's Furnace 1 and 2 added numbers three and four to the circular DC arc ilmenite-smelting application. Although these four furnaces are all circular DC furnaces, the Ticor Furnace 1 and 2 differ in significant respects from the Namakwa Sands furnaces. The main difference being the anode hearth configuration used by Ticor SA, as opposed to the conductive hearth configuration installed by Namakwa Sands. Although the anode hearth configuration is not a new application in the steel and other industries[2,3], its application in a continuous smelting process other than that at Ticor SA is rare.

The extended ramp-up curve of Furnace 1 (shown in Figure 5) can be primarily attributed to overheating of the anodes, with subsequent reduced feed rates and frequent extended downtimes. This poor performance was augmented in the case of Furnace 1, as the ranges of the key operating parameters still had to be determined. This necessitated a steep learning curve regarding the control of the mass and energy balance within the furnace. Establishing and maintaining the mass and energy balance during ilmenite smelting is paramount to ensure sustainable production.

Implementation of the design changes, and significant improvements achieved in maintaining the mass and energy balance of the process, enabled production by Furnace 2 to average above 70% of nameplate capacity by April 2005 – three months after commissioning of its second campaign (see Figure 5).

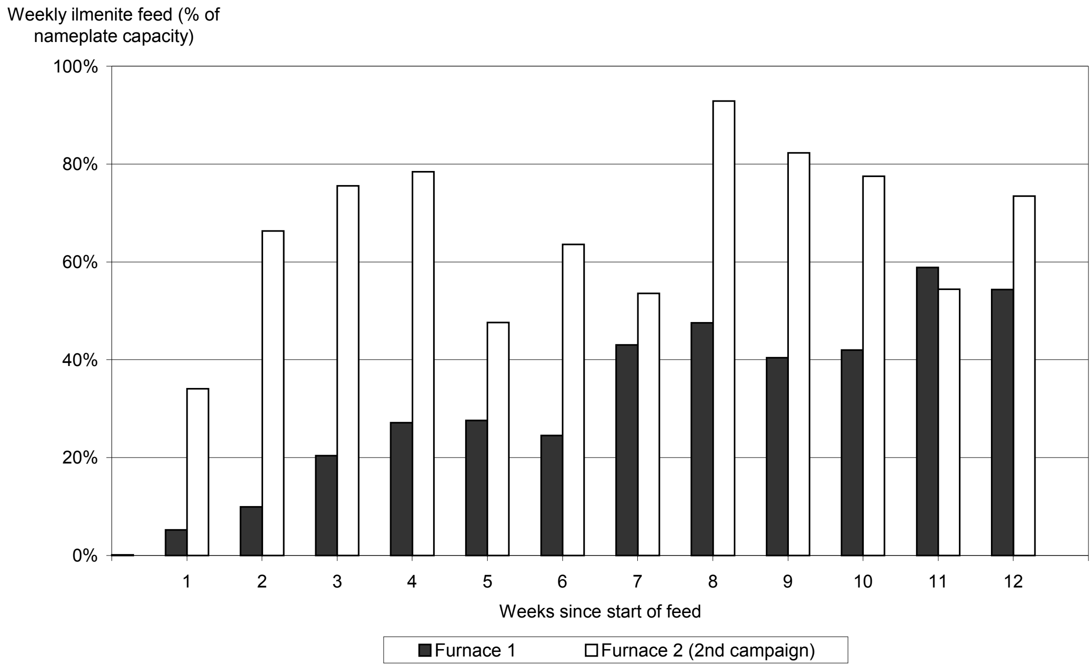

Figure 5: Ramp up curves – expressed as percentage of nameplate capacity of Furnace 1 and Furnace 2 (2nd campaign) compared

FUTURE PLANS

Further commissioning activities include that of two ilmenite pre-heaters – one per furnace. Preliminary successes were achieved on the initial commissioning of Pre-heater 1, and, following modifications to Pre-heater 2, commissioning of the latter is planned for the first half of 2006. By using pre-heating it should be possible to improve the furnace capacity significantly.

The focus is, however, moving from commissioning to stabilisation and improvement of existing processes. This will revolve around a product-specific KPI (Key Performance Indicator) tree (shown in Figure 6) through which focus areas are defined. Focus areas are typically those indicators for which the actual performance lags behind the target. These gaps are to be closed through a focused approach within the entire organisation, by standardisation of activities, idea generation, and implementation. In addition to a support system, this process must be supported by programmes to establish this culture in the organisation. Again the learning curve starts.

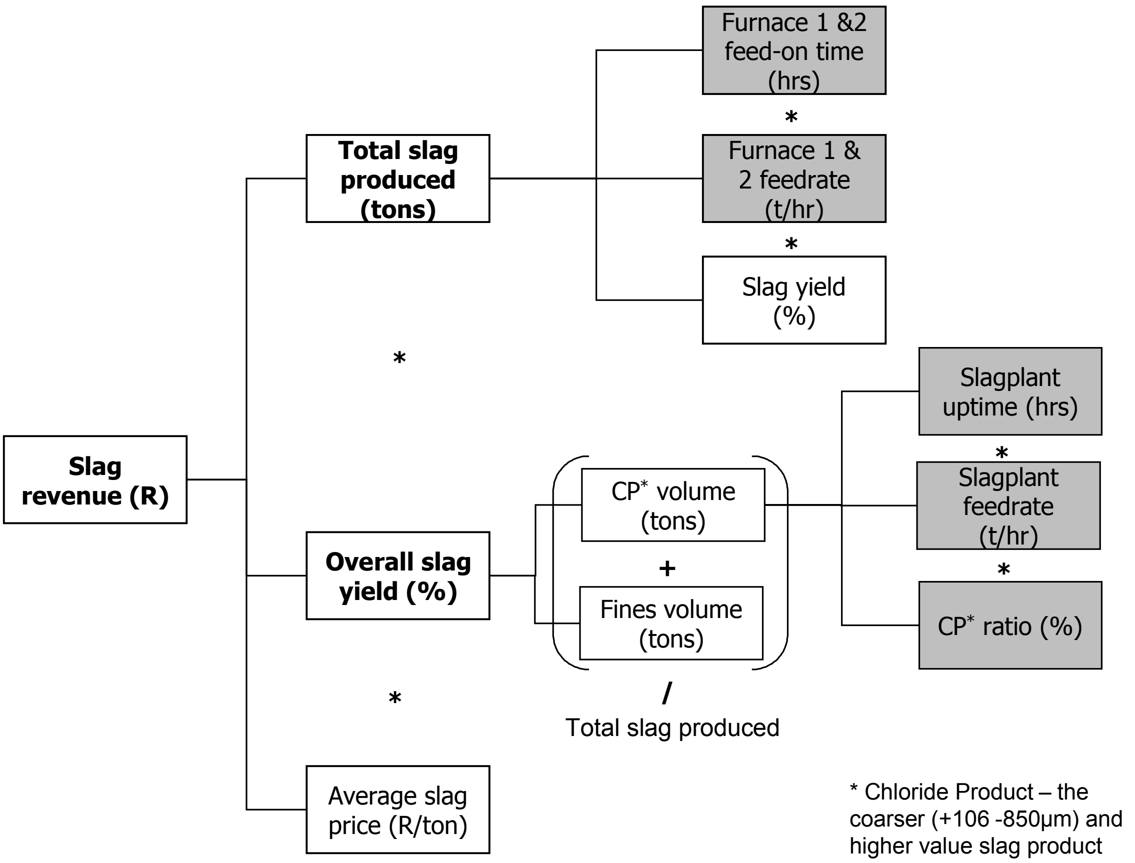

Figure 6: Key Performance Indicator tree for TiO_2 slag revenue

REFERENCES

1. F.H. Norton, *Refractories*, 4th Edition, McGraw Hill Book Company, 1968.
2. A.H. Castillejos, F.A. Acosta, M.A. Pedroza, and M.A. Herrera, A thermal study to improve the lifetime of billet-type bottom electrodes of DC electric arc furnaces: Part 1 – Melting of the metallic charge, *I&SM*, October 2001, pp.61-71.
3. A.H. Castillejos, F.A. Acosta, M.A. Pedroza, and M.A. Herrera, Analysis, design and performance of bottom anodes of DC furnaces, *Proceedings of the Brimacombe Memorial Symposium*, (Eds. G.A. Irons and A.W. Cramb), Vancouver, Canada, 1-4 October 2000, pp.451-465.