

**COAL UTILISATION AT HIGHVELD STEEL
AND VANADIUM CORPORATION**

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HIGHVELD STEEL AND VANADIUM CORPORATION

INTRODUCTION

Based on pilot plant work over a 2 year period, it was discovered that the titaniferous magnetite ore from the Bushveld Igneous Complex could be processed successfully to produce liquid pig iron and vanadium bearing slag and Highveld Steel & Vanadium Corporation was built.

The first liquid pig iron was produced in Iron Plant One in February 1968. Highveld Steel then consisted of 4 pre reduction kilns, 4 submerged arc furnaces, a steelmaking plant, 3 continuous casting machines and a medium / heavy structural universal section mill.

Today the corporation has grown into a diverse group of divisions, producing over a million tons of steel a year, various alloys and packaging material.

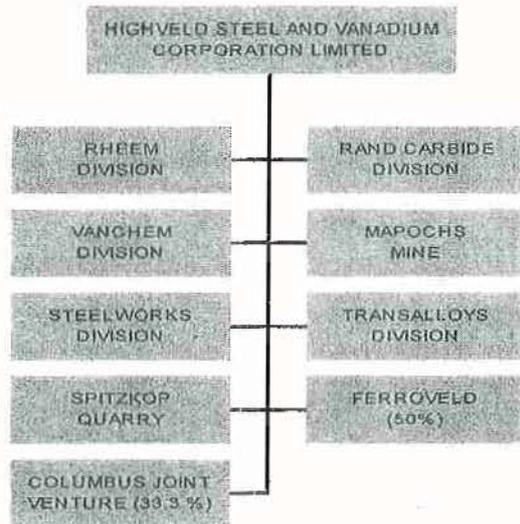


Figure 1 : Corporate Structure of Highveld Steel & Vanadium Corporation

Carbon is a major raw material used within the corporation and forms the backbone of many metallurgical processes.

A diverse range of carbon products are used throughout the corporation. Carbon products used in each division are shown in table 1.

Table 1 : Carbon products used in Highveld Divisions

<i>Plant</i>	<i>Carbon products used</i>
Transalloys	Metallurgical coal Coke
Rand Carbide	Metallurgical coal Electrode paste Char
Steelmaking Ironmaking	Anthracite Anthracite Pulverized coal Metallurgical coal Coke Electrode paste

TRANSALLOYS

Transalloys produces mainly refined ferromanganese and silicomanganese. Refined ferromanganese is produced by the reaction of silicomanganese with a melt of manganese ore and burnt lime.

Silicomanganese is produced by direct reduction of manganese ore and quartzite by coke and coal. High-grade slag from the process is used as an alternative source of manganese and the

furnace burden is completed by the addition of fluxes. Both alloys are cast, crushed and screened before the despatch.

Transalloys supplies Highveld's manganese alloy requirements, but the major proportion of this product is exported.

RAND CARBIDE

Rand Carbide produces 70 - 75 % ferrosilicon and 75 - 80 % ferrosilicon in three submerged arc furnaces with a total capacity of 55 000 tons a year. The raw materials used are quartzite, millscale, wood chips and metallurgical coal.

Rand Carbide also produces a range of carbonaceous products including electrically calcined anthracite, electrode paste and char.

Electrically calcined anthracite is produced in seven resistance type electric furnaces. The anthracite raw material is devolatilized and, to a small degree, graphitised. This material is mainly produced for the use in the production of electrode paste.

Electrode paste is made by combining carefully sized electrically calcined anthracite and a specially produced pitch binder. Rand Carbide paste is used in a wide variety of electric furnaces in Southern Africa.

Char is produced in five moving bed stokers. This material is used as a reductant in electric furnace operations.

STEEL PLANT

Liquid iron is delivered from the iron plant to the steel plant in rail-mounted hot metal ladles. The ladles are emptied into a series of shaking ladles. After scrap has been added, the ladles are placed into one of the four shaking ladle emplacements.

Steelmaking- Shaking ladle

The shaking ladle could be considered as the heart of Highveld. The objectives of the shaking ladle operation are :

1. The production of a dry spinel-type slag containing more than 23 % V_2O_5 , vanadium pentoxide.
2. The maximum recovery of the vanadium contained in the liquid iron.
3. The maximum yield of iron from the steel scrap and liquid iron charged.
4. The production of blown metal having sufficiently high temperature and carbon content to convert in the BOF.
5. The melting of a high ratio of steel scrap to liquid iron for increasing the output of liquid steel.

Mill scale and anthracite are added during the oxygen blow to control the temperature and the carbon content of the liquid iron.

The bath temperature must be less than 1400°C for a high rate of vanadium recovery and a low rate of carbon oxidation to be achieved. To dissipate the heat from the oxygen impact area, the metal is agitated by the shaking motion this has the additional advantage in that it gives proper mixing.

Anthracite is added to make up for the carbon losses in the bath. The anthracite has to have a ash content of less than 12 % and has to be low in Calcium Oxide content.

After the extraction of vanadium as a solid spinel, the metal is taken to one of the three basic oxygen furnaces. A scrap metal charge is added and oxygen is blown on the hot metal through a water-cooled lance.

The steel is then transferred to the continuous casting plant via the ladle refining stations where temperature adjustments, desulphurisation and final composition adjustments are carried out.

The continuous casting plant consists of five machines :

- one billet machine,
- three larger bloom casters, and
- one slab caster.

Final products after the rolling mills consists of :

- channels, angles, rounds or rails
- universal columns
- parallel flanged beams
- joists and billets
- plate
- coil.

IRONMAKING

Introduction

Ironmaking at Highveld is an unique process because of the special type of ore used. The ore is mined at Mapoch's mine near Roosenekal in Mpumalanga and delivered to Highveld by rail. The iron ore is a titaniferous magnetite ore from the Bushveld Igneous Complex with the analysis shown in Table 2.

Table 2 : Typical analysis of Mapochs Ore

<i>Element</i>	<i>Percentage</i>
Fe	53 %
V ₂ O ₅	1.6 %
SiO ₂	1.5 %
TiO ₂	14 %
Al ₂ O ₃	3.75 %
MgO	1.7 %

The titania content of the ore prohibits the ore from being processed via the conventional blast furnace route which is commonly found in an integrated steel works. In this process, highly reducing conditions cause a high percentage of the titanium oxide to be converted to a high melting point titanium carbonitride which chokes up hearth of a conventional blast furnace.

In order to process this type of ore the following metallurgical conditions have to be met :

- The reducing conditions have to be controlled to avoid too much reduction of TiO₂ to form titanium carbide, but at the same time ensure a satisfactory level of iron and especially vanadium reduction.
- During smelting of the ore the contact with air (oxygen) has to be minimized.

Through pilot plant test work on a series of coals, it was discovered that Greenside no.5 seam was best suited to the Highveld Ironmaking process and was in fact the "only" coal that would work in this process. Typical properties of Greenside no. 5 seam are shown in Table 3.

Table 3 : Typical analysis of Greenside no. 5 seam

<i>PROPERTIES</i>	<i>VALUE</i>
ASH db	13.0

VOLS db	31.1
FIXED C db	55.2
S	0.64
SWELL	1.5 - 2.0
AFT °C	1600
RANK	0.75
VITRINITE	57
VITRITE	29
TOTAL REACTIVES	73

For close to 30 years Highveld has been using Greenside no 5 seam as the only metallurgical coal feed with great success, in 1996 the Greenside no 5 seam was mined out prior to the depletion of this reserve.

Highveld had to start researching an alternative coal source for the process. This research continues to try and optimize coal supplies for this unique process.

The Ironmaking Process

The Ironmaking process is divided into two distinctive processes as shown in figure 2 :

- The pre reduction process in the kilns.
- The smelting of the ore in a submerged arc furnace (SAF).

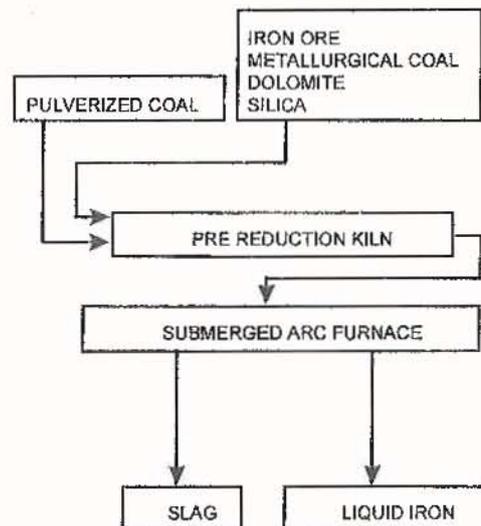


Figure 2 : Flow diagram of the Iron Making Process

Pre Reduction Kilns

The main objective of the pre reduction kilns is to carry out part of the metallurgical work in the solid state using coal as the reducing agent before charging the hot pre-reduced material into the submerged arc furnace. This is done to reduce the consumption of electrical energy and to increase the productivity of the submerged arc furnace.

The Iron making division consists of a total of 13 pre reduction kilns, each with a length of 60 meters and a shell diameter of 4 meters.

Description of the Pre Reduction process

Iron ore, dolomite, silica and metallurgical coal are weighed and charged into the rotary kiln according to a set ratio. When considering each raw material the following needs to be achieved inside the kiln :

- Dry, heat and pre reduce the iron ore (an average of 50 % of the oxygen in the ore removed.
- Dry, heat and char the metallurgical coal (the char formed in the kiln will act as the reductant in the submerged arc furnace)
- Dry, heat and calcine the dolomite

- Dry and heat the quartz

The kilns are fired co-currently using pulverized duff coal. The raw materials and fuel are fed into the kiln at the same end and the material and gas therefore flow in the same direction.

There are 2 distinctive zones in the kiln shown in figure 3.

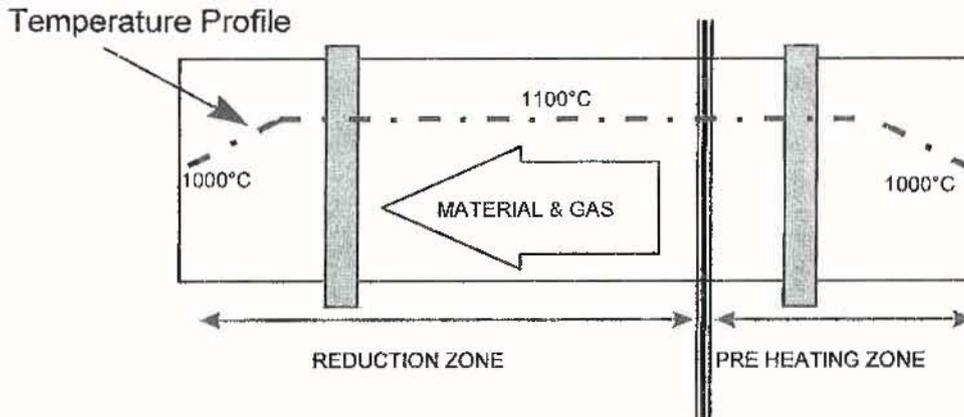


Figure 3 : Two distinctive zones in a kiln and a temperature profile of the kiln.

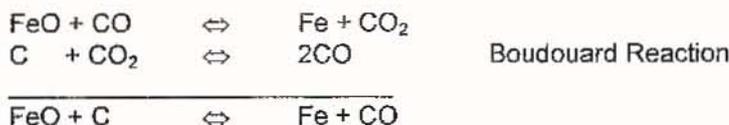
The first zone is the pre heating zone. The combustion of pulverized coal at the inlet supplies the initial thermal energy to heat the kiln so the coal enters directly into a hot area. Initially moisture is driven off of the coal before devolatilization takes place. The mix is also heated to over 900°C so that the reduction process takes place at an appreciable rate.

In the second zone the temperature of the kiln is kept fairly constant at 1100°C and the reduction process proceeds until the mix is discharged into a hopper. Through a series of air pipes along its length, air is introduced into the kiln which combusts with gas that rises through the mix bed and into the free space above the mix. The heat produced from this combustion radiates to the top of the mix bed and heats the exposed kiln wall, which heats the mix as the kiln rotates.

Temperatures should be controlled accurately in this zone. High temperatures can cause sticking of hot material to the sides of the kiln causing gradual build ups which have detrimental effects on the operation as the residence time of the mix in the kiln is shortened and carbon is not consumed, causing high carbon carry over to the SAF.

The reduction of the ore depends on the kiln temperature, filling degree, rotational speed and the reactivity of the metallurgical coal. Most of the reduction will take place at a temperature above 900°C. The reduction process is a solid state reduction, mainly with CO gas. It is important to maintain a protective layer of volatiles or CO gas directly above the mix in order not to have re-oxidation by the kiln exhaust gases in the second part of the kiln.

The main drive for the reduction process depends on the gasification of carbon by CO₂ gas, this reaction is named the Boudouard reaction



The result of the Boudouard reaction is that the heat and carbon consumption is closely linked in the kilns.

In the kiln heat is consumed by :

- Chemical reactions e.g. Boudouard reaction, calcining of dolomite, reduction of ore.
- Heat losses through the shell.

- Heating of the raw materials.
- Devolatilization of the coal.
- Drying of the raw materials.
- Heating of the nitrogen as part of the combustion air injected.

Carbon is consumed by :

- Boudouard reaction
- Combustion of coal with oxygen.
- Direct reduction of ore.
- Unreacted carbon in off gas.

Due to the endothermic nature of the gasification of carbon by CO_2 gas , a large amount of energy is needed before the process initiates, a high temperature is required for the reaction to proceed at an appreciable rate.

The rate of gasification of carbon by CO_2 gas depends on the reactivity of the carbon, the temperature of the kiln and the availability of energy to maintain the process at a suitable temperature. Investigations have also shown that the CO gas formed by the Boudouard reaction is consumed as fast as it is produced, making the Boudouard Reaction the rate controlling reaction of the whole pre-reduction process.

The reactivity of coals varies widely from one source to another. The available surface area on the carbon particle provides reaction sites for the CO_2 gas to react and is the most important factor controlling the gasification reaction. The available surface area is a function of the particle size and the porosity of the coal. Too fine a size of coal is unacceptable as large sized char is required to successfully complete the reduction process in the SAF, thus the porosity of the coal and the subsequent char are the most important factors to consider when determining the reaction surface area. A coal with a high amount of reaction surface area is then ideal for the reduction process in the kiln.

The rate of gasification of carbon by CO_2 gas can be inhibited by the presence of certain elements like sulfur which slows the gasification reaction down. Thus quality control in terms of sulfur in the coal is important for the reduction process.

A typical temperature profile along the length of the kiln is shown in figure 3.

The temperatures are measured by thermocouples every 5 meters along the kiln, reaching 10-25 cm inside the lining. Maximum temperatures are limited so that mix will not enter the softening phase and cause sticking of raw materials to the kiln walls. Temperatures are controlled mainly via the amount of combustion air injected into the kiln.

An important additional parameter for the coal is the ash fusion temperature, this should typically be at least 100 - 150°C higher than the highest operating temperature.

Coals that are used at Highveld with the most success are ortho-bituminous (medium rank C) types of coal , with a minimum AFT of 1300°C. Although the CO_2 reactivities are not determined a high reactive (CO_2 reactivity) coal is ideal.

Submerged Arc Furnace (SAF)

The main objectives of the smelting operation in the SAF are firstly to melt the raw materials to form liquid iron and slag and secondly to reduce the vanadium pentoxide in the ore and dissolve the vanadium into the liquid iron. The operation of the SAF is controlled by both electrotechnical and metallurgical conditions.

There are 7 submerged arc furnaces at Highveld with details shown in table 4.

Table 4 : Submerged arc furnace details

	<i>Iron Plant 1</i>	<i>Iron Plant 2</i>
Number of SAF's	6	1

Normal Rating	415 tons per day	600 tons per day
Transformer rating	4 x 45 MVA 2 x 33 MVA	63 MVA
Furnace Diameter	14 m	15.6 m
Electrode Diameter	1.600 m	1.800 m
Normal power input	24 MW	36 MW
Tap to Tap Time	3.5 to 4 hrs	3.5 to 4 hrs
Tap Weight	70 tons	80 tons
Number of tapholes	2	2

The SAF is charged with hot pre reduced mix from the kilns.

SAF's are low shaft furnaces and significantly less gaseous reduction of the ore occurs, leaving the bulk of the reduction to take place in the solid state which requires significantly higher amounts of energy.

Practically all heat is provided by electrical resistance and arc heating. The pre reduction of the mix charged has a significant influence on the electrical consumption of the SAF. With higher pre reductions the electrical consumption decreases and productivity increases. Higher pre reduction has a disadvantage in that the carbon content of the liquid iron decreases, which results in skulling problems in the transfer ladles.

The electrical resistance of the charge is a critical factor in the SAF operation. The main electrical variable is the ohmic resistance at the electrodes. In our effort to control the electrical conditions, we have to consider the metallurgical factors which influence the charge resistance.

Important features of smelting titaniferous ore are :

1. Carbon in the SAF has dual function, firstly as a reductant for the oxides and secondly as a source of carbon for the carbonizing of the liquid iron.
2. In order to maintain the optimum smelting conditions inside the SAF it is essential to exercise accurate carbon control. Experience has shown that this is very difficult to achieve and maintain.
3. Very fine mix is charged into the SAF, as a result of the processing in the kilns. Up to 50 % of the mix charged is -6mm material. This can lead to poor gas permeability and slag boils occurs occasionally.
4. The high TiO_2 content of the ore requires a high slag volume to ensure that the TiO_2 reports to the slag and not the iron. The high slag bulk increases the energy consumption. Operation on high TiO_2 slags requires very careful control of the carbon balance. Surplus of carbon will tend to reduce TiO_2 to lower oxides and even form titanium-carbides, each of which forms a difficult viscous slag. A deficiency of carbon in the charge will give poor vanadium recovery.

There has been little study of the ideal properties of the coal and char that could be used in the Highveld process. Through trial and error in the plant environment we have gained a good understanding of the type of coal that "works" in this process.

Through experience some of the general conclusions that can be made about the SAF operation:

1. The most important factor in the SAF operation is the necessity for a carbon source that can be easily absorbed into the liquid iron, without negatively disturbing the electrical conditions in the furnace. A net build-up of carbon in the SAF, drives the electrodes out of the furnace, cooling it down and affecting both the chemistry and production of the furnace.
2. A carbon source with a good wettability to liquid iron would be the ideal as this would probably result in a more favorable dissolution rate of carbon into the liquid iron.
3. On an atomic scale a highly structured carbon form would disassemble its structure rapidly. A C-atom can "unzip" a whole plane of C-atoms associated to it. This would lower the amount of energy required to dissolve the C-atoms in the liquid iron. For a disordered type of carbon structure the removal of a carbon atom requires the same amount of energy when removing the first atom in the ordered carbon structure, but the subsequent C atoms are not removed as

easily as the ordered carbon form and each individual C atom has to be removed one by one. This requires large amounts of additional energy and the reaction rate is slower than that for an ordered structure.

DISCUSSION : COAL QUALITY OF COAL SUITABLE FOR USE IN IRONMAKING

Pulverized Coal

The function of the pulverized coal is to supply sufficient energy at the inlet part of the kiln to dry the metallurgical coal and start the devolatilization process the instant that the coal is introduced into the kiln.

The properties that have been identified for duff coal used to produce the pulverized coal are :

- Coal must be milled to produce the correct fineness.
- Ignition must be fast.
- Devolatilization is to start and end very rapidly.
- Good flame stability with a constant point of ignition near the burner.
- Combustion at a even rate to provide sufficient energy along the whole length of the kiln.
- Coal should be completely combusted when exiting the kiln.
- High ash softening point to prevent build ups forming in the kiln.
- Low ash content

Observation of the process with different types of coal has shown that highly reactive coal have the advantage that they will ignite fast in the inlet part of the kiln and supply the necessary energy to heat and dry the raw materials. The disadvantage is that the coal is fully combusted half way through the kiln and therefore cause a drop in the kiln temperatures near the discharge end which can affect the reduction process negatively.

A low reactive coal does not supply sufficient energy at the inlet of the kiln and the start of the reduction process is delayed, causing poor pre reductions. Due to uncompleted combustion, large amounts of pulverized coal report to the off gas system resulting in inefficient use of carbon. The advantage is that there is an adequate supply of energy at the kiln outlet.

Metallurgical Coal

The function of the metallurgical coal are to provide the carbon source for the pre reduction of the ore in the kiln, further reduce the ore in the furnace and to supply the carbon to the liquid iron produced in the furnace.

The properties that have been identified for metallurgical coal used in the kiln are :

- High reactivity coal (reactivity with CO₂ gas)
- Coal to produce a strong char to carry over to submerged furnace

SAF OPERATIONAL OBSERVANCES

A high pre reduction can also cause difficulties with the carbon content of the iron. If low reactive coals are used, the coal does not burn or react in the kiln and we have a large carbon carry over to the SAF, this causes the furnace to have an excess of carbon and the electrodes are driven out of the furnace. If a highly reactive coal is used, a large proportion of the carbon is consumed in the kiln and the resultant carbon content of the iron is low, leading to an increase in the liquidus temperature of the iron and skulling of the transport ladles occurs.

Rules of thumb for ironmaking are :

- Different types of feed coal will produce different types of chars and these chars can influence the resistance.
- The resistance generally decreases when the temperature of the feed charge increases.
- The resistance generally decreases when the pre reduction of the feed charge increases.

- Electrode penetration also affects the resistance significantly.

From recent experience it has been observed that the process cannot operate on only one type of coal. Typical petrographic analyses of coals currently used are shown in table 5.

Petrographic analysis has indicated that coals within a relatively narrow range are suitable for use and the factors which we consider when evaluating the quality of the coal are :

- Vitrinite and vitrite
- Inertinite
- Total reactives
- Rank

Lower vitrinite and vitrite content coals are generally coals that perform well in the kilns and produce good pre reductions. The reactivity of these coals with CO₂ seems to be higher, producing enough CO gas for pre reduction.

Table 5 : Petrographic analyses of coals currently used.

Colliery	Forzand o	Golf View	Greenside	Lakeside	Leeufontein	Rietspruit	Rondebul t	Tavistock	Woestalleen
Seam	4		5	2	2	5	2	5	2
% VIT (Vitrinite)	53	62	58	32	30	55	24	55	31
% TV (Total Vitrinite)	57	67	59	33	32	56	25	58	31
% TOTAL	71	76	74	55	55	71	52	70	54
REACTIVES									
Rank % Rr (Random reflectance)	0.63	0.6	0.75	0.64	0.61	0.72	0.77	0.68	0.67
Rank - degree of Maturity	ortho- bitumin.								
ECE-UN In Seam Classification	Med. Rank C	Med. Rank C	Med. Rank C	Med. Rank C	Med. Rank C	Med. Rank C	Med. Rank C	Med. Rank C	Med. Rank C
V-class distribution	V5-V9	V5-V7	V6-V9	V5-V7	V4-V7	V5-V8	V5-V8	V5-V7	V5-V9
Visible minerals	low clays								
Swelling No.	1	1.5	2	0.5F	0.5F	1	1	1	0.5F
Ash Fusion Temperatures	1340	1380	+1600	1520	1360	1510	+1600	1530	+1600

Higher vitrinite and vitrite content coals are generally associated with coals that form char that is critical for the proper operation of the SAF.

A feed blend with too high a vitrinite content and a low inertinite content has very little carry over to the furnace and under carbon conditions occur.

A feed blend with low vitrinite and high inertinite content seems to carry over a lot of unreacted coal to the SAF and the carbon does not react, resulting in a build up of carbon . This results in a change in the resistance of the mix and generally drives the electrodes out of the furnace, reducing the power input to the SAF and the SAF cools down and the performance is lowered.

Current operation includes the blending of low and high vitrinite coals, which are fed through the entire process.

Operation philosophy is starting to change towards looking at how to blend the different coals to achieve proper functioning in the kilns and in the SAF. Future plans include the splitting up of the two processes in terms of the coals used so that a specific coal is used in the kilns and then another coal is fed into the SAF for that operation.

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