

Economic feasibility of a pre-oxidative process to enhance solid-state chromite reduction

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DECLARATION

I, **Ernst Lodewyk Johannes Kleynhans**, hereby declare that the dissertation entitled:

Economic feasibility of a pre-oxidative process to enhance solid-state chromite reduction,

is my own work and has not been submitted to another tertiary institution in whole or in part.



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Potchefstroom

November 2015

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“The words of the wise are as goads, and as nails fastened by the masters of assemblies, which are given from one shepherd. And further, by these, my son, be admonished: of making many books there is no end; and much study is a weariness of the flesh. Let us hear the conclusion of the whole matter: Fear God, and keep his commandments: for this is the whole duty of man. For God shall bring every work into judgment, with every secret thing, whether it be good, or whether it be evil.” Ecc 12:11-14 (KJV)

† *My Heavenly Father, thank you for blessing me daily and giving me the ability and perseverance to successfully complete this research. Thank you for your grace and love, for keeping an eye on me and guiding me throughout my life.* †

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Dr Pieter van Zyl



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Prof Piet Stoker

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GLENCORE

My parents, Ernst and Yvette, and my siblings Albert and Ingrid, thank you for your love, never-ending support and encouragement.

❧ My best friend and wife, Anzel Kleynhans ❧

“I may not have everything I want in life but I’m blessed enough to have all that I need!”

PREFACE

Introduction

This dissertation was submitted in article format, as allowed by the North-West University (NWU) under the Academic rules (A-rules) set for post-graduate curriculums (NWU, 2014). The A-rules prescribe that "where a candidate is allowed to submit a dissertation or mini-dissertation in the form of a published research article or articles or as an unpublished manuscript or manuscripts in article format, the dissertation or mini-dissertation must still be presented as a unit, supplemented with an inclusive problem statement, a focused literature analysis and integration and with a synoptic conclusion, and the guidelines of the journal concerned must also be included." This entails that the article is added into the dissertation as it was drafted for submission to a journal, submitted to a journal or accepted for publication depending on which stage of the journal publication process the article is in when the dissertation is submitted for examination. The conventional experimental as well as results and discussions chapters are therefore excluded, since the relevant information is summarised in the article. Separate background and motivation or problem statement, literature and project evaluation chapters were included in the dissertation along with the article, as set out in the Manual for Post Graduate Studies (NWU, 2013) guidelines for submitting a dissertation/thesis in article format. As some of the information of the problem statement, literature and project evaluation chapters were summarised in the article, this will result in some repetition of ideas/similar text in some of the chapters and in the article itself.

Rationale in submitting dissertation in article format

Although submitting a dissertation in article format is allowed by the NWU, it is currently not a requirement under the A-rules of the NWU. However, it is prescribed in the A-rules that with the submission of any dissertation or mini-dissertation which is not submitted in the form of a series of manuscripts in article format, faculty rules may also require proof that at the time of submitting the dissertation/thesis for examination, the candidate prepared a draft article ready for submission or already submitted a research article to an accredited journal. In practice, many of the draft papers are never submitted for peer reviewed publication in an accredited journal.

There are several advantages to write a dissertation/thesis in article format:

- It resolves the conflict between preparing the thesis for examination and preparing papers for publication, as they amount to the same outcome. Generally writing of the dissertation enjoys priority, which results in a lot of dissertations and thesis's not getting published and prevented from greater exposure to the public domain.
- As touched on in the aforementioned it increases the probability that the work conducted for the purpose of the degree is published. This is not only to the advantage of the candidate, but also that of the supervisor(s), contributors and the university.
- If the candidate submits and receives reviewers' comments on the article(s) before submitting the dissertation/thesis for examination, the candidate can use this feedback to improve the dissertation/thesis. This not only improves the quality of the dissertation/thesis, but also gives the candidate a greater confidence in the work conducted. By the time the dissertation/thesis is submitted for examination, the core part of the dissertation/thesis has already been subjected to the scrutiny of experts other than the candidate and his supervisor(s).
- Having part of the work published prior to examination establishes it as worthy of publications, which is one of the requisite criteria for a PhD degree, but not a master's degree. Therefore the larger the portion that is published, the easier it is for the examiners of the dissertation/thesis and the Board of the Graduate Research entity to recognise that the work is substantial and of value, more so in the case of work on masters level being published.

Contributions to the article and co-authors consent

Authors of the article

The co-authors of the above-mentioned article (Chapter 4) were:

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Contributions

The bulk of the work was done by the candidate ELJ Kleynhans, with conceptual ideas and recommendations by the supervisors JIJ Fick and JP Beukes, as well as by PG van Zyl.

Co-authors consent

All the co-authors of the article had the opportunity to comment on the article as included in Chapter 4 and gave consent that it can be included in this MEng dissertation.

Formatting and current status of article

The article was formatted in accordance to the journal specifications to which it was submitted, i.e. *The Journal of The Southern African Institute of Mining and Metallurgy*. The author's guide that was followed in preparation of the article was available at <http://www.saimm.co.za/guidelines-for-authors> (Date of access: 17 November 2015). The article was submitted for review on 20 November 2015.

Curriculum option

The Masters' degree programmes in the Engineering faculty of the NWU allow for two options. These options allow different combinations of coursework and/or research that are based on an engineering problem leading to a synthesised solution based on engineering methods and designs.

The two options can be summarised as follows:

	OPTION A	OPTION B
Description	Comprehensive research-based full dissertation	Coursework & research- or project-based dissertation
Credits (Total of 180 credits)	Full Research Dissertation: 172 Research Methodology: 8	Research Dissertation: 92 <i>(Approx. half of a full dissertation)</i> Research Methodology: 8 Plus 5 x 16-credit modules: 80

The candidate, in terms of this dissertation and for the purpose of partial fulfilment of the requirements for the degree Magister in Ingeniaria (MEng) in Development and Management Engineering at the Potchefstroom Campus of the NWU had chosen the curricula option, Option B, comprising of coursework (modules) and a research- or project-based dissertation. The candidate has, as required by the Engineering faculty and NWU, completed all the coursework modules upon submission of this dissertation for examination.

ABSTRACT

Chromite ore mining is the only commercially viable source of new chromium (Cr) units. South Africa (RSA) holds the majority, approximately 75%, of the world's exploitable chromite ore resources. The vast majority of mined chromite, approximately 90–95%, is consumed by the metallurgical industry for the production of different grades of ferrochrome (FeCr). The stainless steel industry consumes 80–90% of FeCr, primarily as high-carbon or charge grade. FeCr is vital to the production of stainless steel, an essential material in modern-day society of which the application and demand are growing. FeCr production is energy intensive, with huge amounts of electricity being consumed in the smelting process. In RSA, in particular, significant increases in electricity prices have placed pressure on FeCr producers. The pelletised chromite pre-reduction process is most likely the FeCr production process with the lowest specific electricity consumption (SEC), i.e. MWh/ton FeCr, currently in operation. However, due to increases in costs, efficiency and environmental pressures, FeCr producers applying the aforementioned process are still attempting to achieve even lower overall energy consumption. Recently it was proven that pre-oxidation of chromite ore, prior to pelletised pre-reduction, significantly decrease the SEC and lumpy carbonaceous reductants required for furnace smelting by increasing the process pre-reduction levels. Higher chromite pre-reduction levels correspond to lower furnace specific electricity and lumpy carbonaceous reductant consumption. This dissertation presents the first attempt at conceptualising the techno-economic feasibility of integrating chromite pre-oxidation into the current industrially applied pre-reduction process. Financial modelling yielded a net present value (NPV) of ~ZAR 1.9 billion at a 10% discount rate and an internal rate of return (IRR) of ~51%, suggesting that implementation of pre-oxidation prior to pelletised pre-reduction may be viable from a financial perspective. Sensitivity analysis indicated that the parameter with the greatest influence on project NPV and IRR is the level of pre-reduction achieved. This indicated that the relationship between maintaining the optimum pre-oxidation temperature and the degree of pre-reduction achieved is critical to maximise process efficiency.

Keywords: Chromite pre-reduction, Solid state reduction of chromite (SRC), Pre-oxidation of chromite, Discounted cash flow (DCF) model, Techno-economic feasibility

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LIST OF ABBREVIATIONS

Academic rules	A-rules
Bushveld Igneous Complex	BIC
Chromium	Cr
Direct current arc furnace	DCF
Electricity Supply Commission of South Africa	Eskom
Ferrochrome	FeCr
Gross domestic product	GDP
Internal rate of return	IRR
International Chromium Development Association	ICDA
Iron	Fe
Net present value	NPV
North-West University	NWU
Platinum group metals	PGMs
Revenue clearing account	RCA
South Africa	RSA
South African Rand (currency)	ZAR
Specific electricity consumption	SEC
Submerged arc furnace	SAF
United States Geological Survey	USGS

CHAPTER 1: MOTIVATION AND OBJECTIVES

An overview of the motivation and aims for investigating the techno-economic feasibility of integrating a chromite pre-oxidation process into the currently applied chromite pre-reduction process is provided in this chapter. In § 1.1 the problem statement and research proposal, together with background information are presented, while the objectives are listed in § 1.2.

1.1 Research project motivation

1.1.1 Problem statement and research proposal

South Africa's (RSA) ferrochrome (FeCr) production has been rapidly declining from 2008 (ICDA, 2013d), resulting in substantial losses in gross domestic product (GDP) and job creation opportunities (Merafe-Resources, 2012). The main reason behind this production decrease is RSA's insufficient electricity generation capacity. Eskom, RSA's state controlled monopolistic energy supplier, realised that their unable to support the growing total electricity demand and agreed to pay FeCr smelters not to use already contracted energy, if they lowered production and put future operational expansions on hold. A newly proposed process to pre-oxidised chromite ore prior to being used as feed for the pelletised chromite pre-reduction process (also referred to as solid-state reduction of chromite) showed significant potential to reduce specific electricity consumption (SEC) during FeCr production (Neizel, 2013; Beukes *et al.*, 2015; Kleynhans *et al.*, 2015). With RSA's current electricity situation expected to continue for the foreseeable future and a global shift in mind-set to reduce energy usage, it would be beneficial to South African FeCr producers to investigate the economic feasibility and implementation possibility of this energy saving technology.

1.1.2 Background

Chromite ore mining is the only commercially viable source of new chromium (Cr) units (Cramer *et al.*, 2004; Beukes *et al.*, 2010; Murthy *et al.*, 2011). Approximately 90–95% of mined chromite is consumed by the metallurgical industry for the production of different grades of FeCr. The stainless steel industry consumes 80–90% of FeCr, primarily as high-carbon or charge

grade FeCr (Abubakre *et al.*, 2007; ICDA, 2013d; ICDA, 2013c). FeCr is mainly produced by means of pyrometallurgical carbo-thermic reduction utilising primarily alternate current submerged arc furnaces (SAF) and direct current arc furnaces (DCF) (Beukes *et al.*, 2010; Dwarapudi *et al.*, 2013; Neizel *et al.*, 2013). This smelting production process is an energy-intensive process consuming not only high quantities of electricity, but also large amounts of coal based reductants (Holappa, 2010; Ugwuegbu, 2012; Pan, 2013). RSA, with the world's largest chromite deposits located in its Bushveld Igneous Complex (BIC), holds ~72% of global chromite reserves (~82% when the upper group two (UG2) reserves of the platinum mines is added) and has an estimated FeCr production capacity of 5.2 million t/y (Beukes *et al.*, 2012; Merafe-Resources, 2012; Creamer, 2013; Jones, 2015). Until 2011, RSA was the largest FeCr producer in the world, with about 33% of global production. In 2012, however, it's production decreased to about 30% of the world's output, becoming the second-largest FeCr producer, after China who doubled their production from 2009-2012 (ICDA, 2013d). The factors that lead to RSA's FeCr production decline can all be traced to the countries recent electricity situation characterised by a shortage in supply and sharp price increases (ICDA, 2013b; ICDA, 2013c; Pan, 2013). The cost distribution for South African smelters varies slightly from smelters in European conditions; with chromite ore, reductants, and electricity each accounting for approximately 30% of the production costs in RSA, while factors such as maintenance, labour and waste disposal accounts for the remaining 10% (Biermann *et al.*, 2012). Considering that electricity consumption is one of the single largest cost component in FeCr production (Daavittila *et al.*, 2004), instability in supply and cost increases are extremely significant. The pelletised chromite pre-reduction process (as applied in the Premus process by Glencore Alloys) is considered to be the process option with the lowest SEC, i.e. approximately 2.4 MW h/t FeCr (Naiker, 2007; Kleynhans *et al.*, 2012). When comparing this to DC furnace operations of >4.5 MW h/t FeCr (Greyling *et al.*, 2010), the oxidative sintered process (Outotec process) of >3.1 MW h/t FeCr (Botha, 2003; Naiker, 2007) and conventional semi-open ore fed SAF production of 3.9-4.2 MW h/t FeCr (Naiker & Riley, 2006; Weber & Eric, 2006), it becomes clear that the pelletised chromite pre-reduction process option holds significant SEC advantages, especially within the current South African electricity context (Eskom, 2012; Kleynhans *et al.*, 2012). Various strategies have been investigated to improve the rate of chromite pre-reduction ((Neizel *et al.*, 2013), and references therein), however the approach that is of interest in this study was the process to pre-oxidise the chromite ore prior to pre-reduction, as recently

proposed (Neizel, 2013; Kleynhans *et al.*, 2015). This process showed potential to enhance chromite pre-reduction, thus lowering the overall SEC. Considering the extent of RSA's chromite reserves, the unique characteristics of these reserves and the size of the local FeCr industry, the feasibility of the afore-mentioned process is thus of significant local (but also of international) interest. Therefore, the aim of this study is to explore the economic feasibility of this process within the South African FeCr industry.

1.2 Objectives

The specific aims and objectives of this study were to:

- (i) Conduct a literature survey on the processes involved (solid-state reduction and pre-oxidation), process implementation and integration and the economic environment of RSA's FeCr industry.
- (ii) From literature investigate process approaches to conduct pre-oxidation of chromite prior to pre-reduction and give recommendation with regard to the best approach to conduct pre-oxidation.
- (iii) Conduct an economic feasibility study to integrate a chromite pre-oxidative process as a precursor to the pelletised chromite pre-reduction process.
- (iv) Perform sensitivity analysis on the proposed financial model.
- (v) Make recommendations with regard to future perspectives of the possible further development and implementation of pre-oxidation as a means to improve FeCr production.

CHAPTER 2: LITERATURE SURVEY

In this chapter, an overview of relevant literature is provided. This consists of the importance of the FeCr industry within the South African context (Section 2.1), the main processes and techniques utilised during FeCr production (Section 2.2) and chromite pre-reduction as an energy saving process option (Section 2.3).

2.1 South Africa's ferrochrome industry

2.1.1 Chromite ore resources

Historically, there was sufficient high-grade metallurgical chromite ore to meet demand, however with the rapid growth of the stainless and other alloy steel industries, the much larger reserves of the lower grade-higher iron (Fe) containing ores had to be exploited. Through the years, various terms have been used to describe and classify mineral resources. It is therefore important to correctly define these classifications. The United States Geological Survey (USGS) define resources, reserve base, reserves, and shipping-grade chromite ore as follows (USGS, 2015):

Resource - a mineral in such a form that economic extraction of a commodity from the concentration is currently or potentially feasible.

Reserve base - the part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth.

Reserve - the part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative.

Shipping-grade chromite - the reserve deposit quantity and grade normalised to 45% Cr₂O₃.

Global chromite resources are estimated to be between 9.2 and 12 billion tons, which is sufficient to meet demand for centuries. The geographical locations and size of major chromite resource deposits, acquired from Kogel *et al.* (2006), are illustrated in Figure 2–1, along with

the global chromite ore reserve base, presented in Table 2–1 (Pariser, 2013). According to various sources RSA holds between 68% and 80% of the world’s economically viable chromite ore resources (Howat, 1986; Cowey, 1994; Riekkola-Vanhanen, 1999; Cramer *et al.*, 2004; Basson *et al.*, 2007; Lungu, 2010; OCC, 2014). Large resources and reserves are also located in Zimbabwe, with smaller resource deposits situated in Kazakhstan, Canada and Turkey.

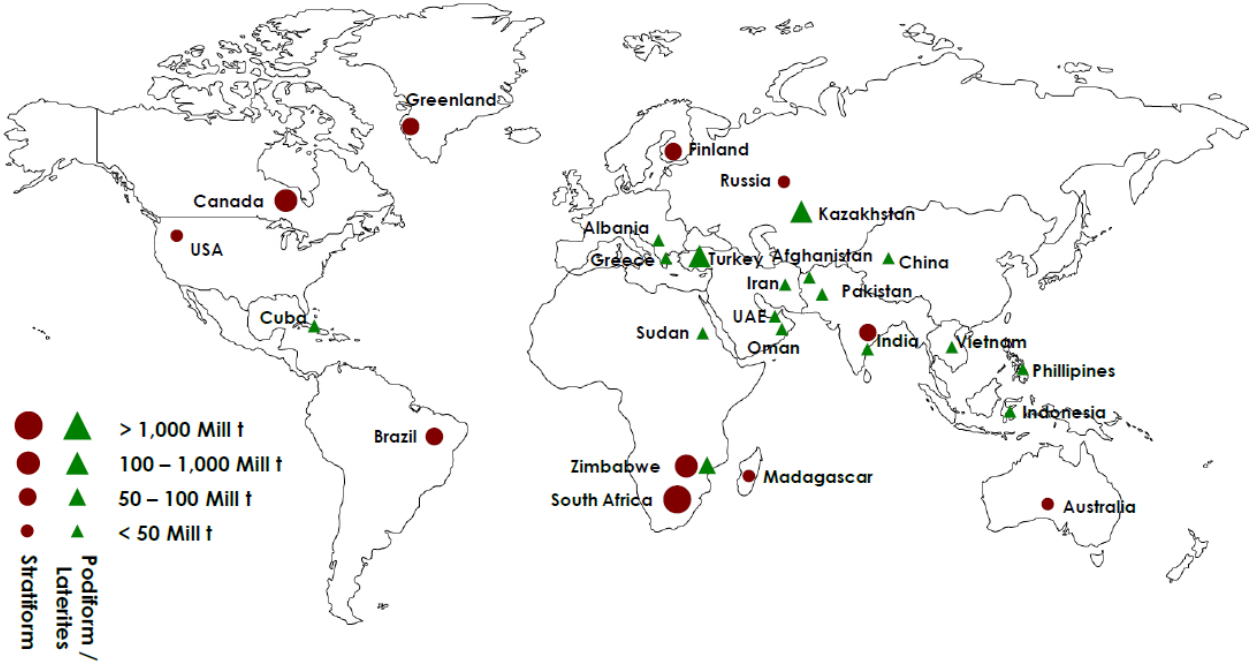


Figure 2–1: Geographical location, geologic type and size of major chromite ore resource deposit (Kogel *et al.*, 2006; Pariser, 2013; OCC, 2014)

Table 2–1: World Chromite Ore Reserve Base (Pariser, 2013)

	Million metric ton	%
South Africa	6 860	72.71
Zimbabwe	930	9.86
Kazakhstan	387	4.10
Turkey	220	2.33
Canada	220	2.33
Finland	120	1.27
India	54	0.57
Brazil	18	0.19
China	5	0.05
Others	621	6.58
Total	9 435	100

The total world shipping-grade chromite ore reserves were estimated by the USGS at around 480 million tonnes (Basson *et al.*, 2007; Papp, 2008; USGS, 2015). Geologically the world’s chromite ore resources are found in either podiform or stratiform deposits. Podiform-type chromite deposits occur in irregular shapes like pods or lenses, while stratiform-type chromite deposits occur as parallel seams in large, layered igneous rock complexes. The layering is regular and there is large lateral continuity. The largest and best example of this type of deposit is the BIC. RSA’s entire chromite ore resources are located within the BIC where several chromite seams exist (Cramer *et al.*, 2004). Comparisons between selected international reserves, obtained from Pariser (2013), are illustrated in Figure 2–2.

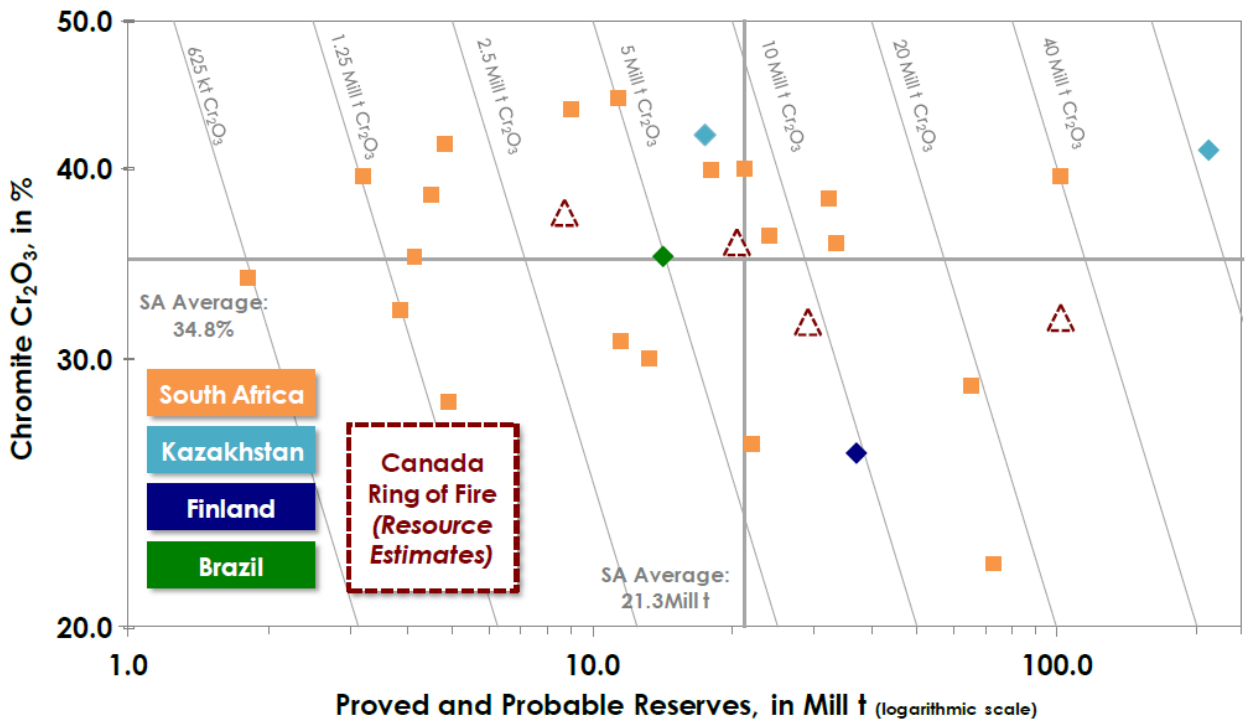


Figure 2–2: International reserve comparison (Pariser, 2013)

RSA’s economically exploitable seams are the lower group 6 (LG6) with a Cr-to-Fe (Cr/Fe) ratio of 1.5-2, the middle group 1 and 2 (MG1 and MG2) with a Cr/Fe ratio of 1.5-1.8 and the upper group 2 (UG2) with a Cr/Fe ratio of 1.3-1.4. The last of these is not of interest as a source of chromite alone but primarily as a source of platinum group metals (PGMs). Chromite ores in RSA are therefore associated with PGMs. The major reserves of PGMs are the UG2 and Merensky reefs, which are the largest deposits of Cr, vanadium and platinum in the world (Howat, 1986; Cramer, 2001; Cramer *et al.*, 2004; Xiao & Laplante, 2004; Basson *et al.*, 2007). UG2 chromite ore is gaining acceptance as a source for charge grade FeCr production with the

utilisation of several technological innovations (Basson *et al.*, 2007). One should take note that RSA's *in situ* chromite ores are largely low grade (< 45% Cr₂O₃) with low Cr/Fe ratios (< 1.6) and are generally brittle. The resulting alloys produced from these ores are mostly charge grade FeCr with a Cr content of < 55%. There is also a general requirement for agglomeration of the ore to render it suitable for efficient charge grade FeCr production. The production of charge grade FeCr with lower Cr content also influences the transport cost per Cr unit adversely (Basson *et al.*, 2007).

2.1.2 Economic and market considerations

Worldwide chromite ore demand is primarily dependent upon the usages of FeCr in the stainless and alloy steel manufacturing process. Chromite ore also has some uses in the chemical, refractory and foundry industries, but they provide a far smaller proportion of demand than FeCr production (ICDA, 2013a). In 2011, in spite of steady growth in stainless steel and FeCr production over the previous 5 years (2007-2011) chromite ore prices were lower in nominal terms than they were at the start of 2007. Accounting for inflation during this period, metallurgical grade chromite ore prices actually declined in real terms (ICDA, 2013a). This has been attributed to oversupply with a number of reasons being responsible for ore consumption growing more slowly than aggregate supply over this period, i.e. (i) FeCr furnaces have become more efficient, (ii) technological advances have allowed FeCr smelters to use greater quantities of what once would have been considered low-quality ore (i.e. ore with comparatively low Cr content, low Cr/Fe ratios and higher presence of contaminants such as silicon) and (iii) FeCr producers have also lowered their consumption of lumpy chromite ore, substituting it with pelletised concentrate or, in some cases, directly charging their furnaces with fines. Lower-grade chromite ore is, normally, in greater abundance in addition to being easier and cheaper to produce than higher-grade lumpy ore that it has replaced. As a result, relatively inexpensive supply sources (e.g. UG2) have been developed, and contributed to the excessive supply capacity (ICDA, 2013a).

Chromite ore is mined in over twenty countries, but approximately 82% of the production originates from five countries, i.e. on average during 2001-2012 RSA accounted for ~41% of the world's production, Kazakhstan and India accounted for ~17% and ~15%, respectively, Turkey

for ~6% and Brazil for ~3% (Papp, 2008; Papp, 2009; Anon, 2010c; ICDA, 2013d). The chromite ore production of these five countries is presented in Figure 2–3.

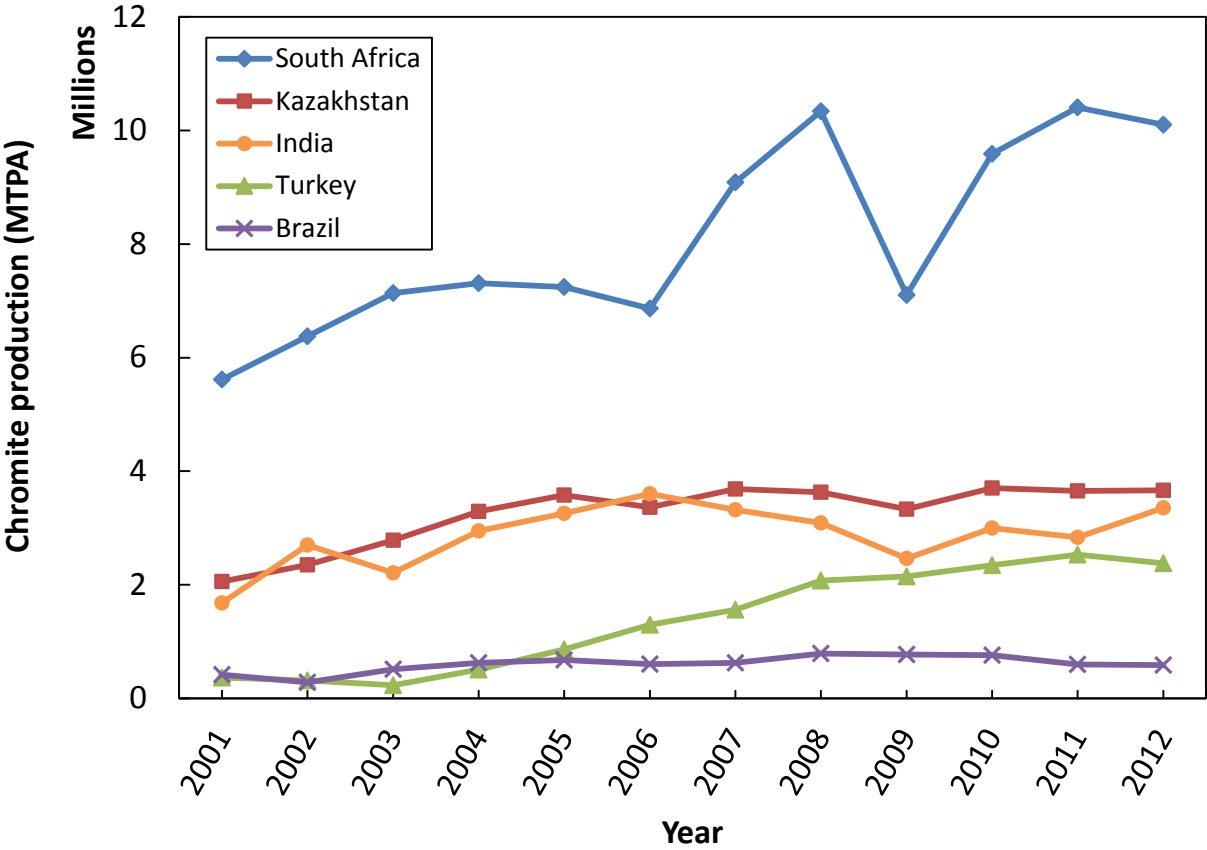


Figure 2–3: Chromite production in million metric tons per annum (MTPA) for 1990-2012 (ICDA, 2013d)

As previously mentioned, the majority of chromite is converted into FeCr, which in turn is mostly consumed for stainless steel production (Anon, 2010a; Anon, 2010c). It is therefore useful to consider the correlation between chromite, FeCr and stainless steel production volumes. Figure 2–4 indicates that there is a direct correlation, with some lags, between the production volume trends of these commodities. From Figure 2–4 it is observed that if the demand for stainless steel increases the demand for FeCr and ultimately chromite ore will automatically follow suit. This will either lead to a supply deficiency and a rise in FeCr prices or an increase in FeCr production, or both.

Cr materials are not openly traded. Purchase contracts are confidential between buyer and seller; however, trade journals report composite prices based on interviews with buyers and sellers, and traders declare the value of materials they import or export. Thus, industry

publications and international trade statistics are sources of Cr material prices and values, respectively (Papp, 2008).

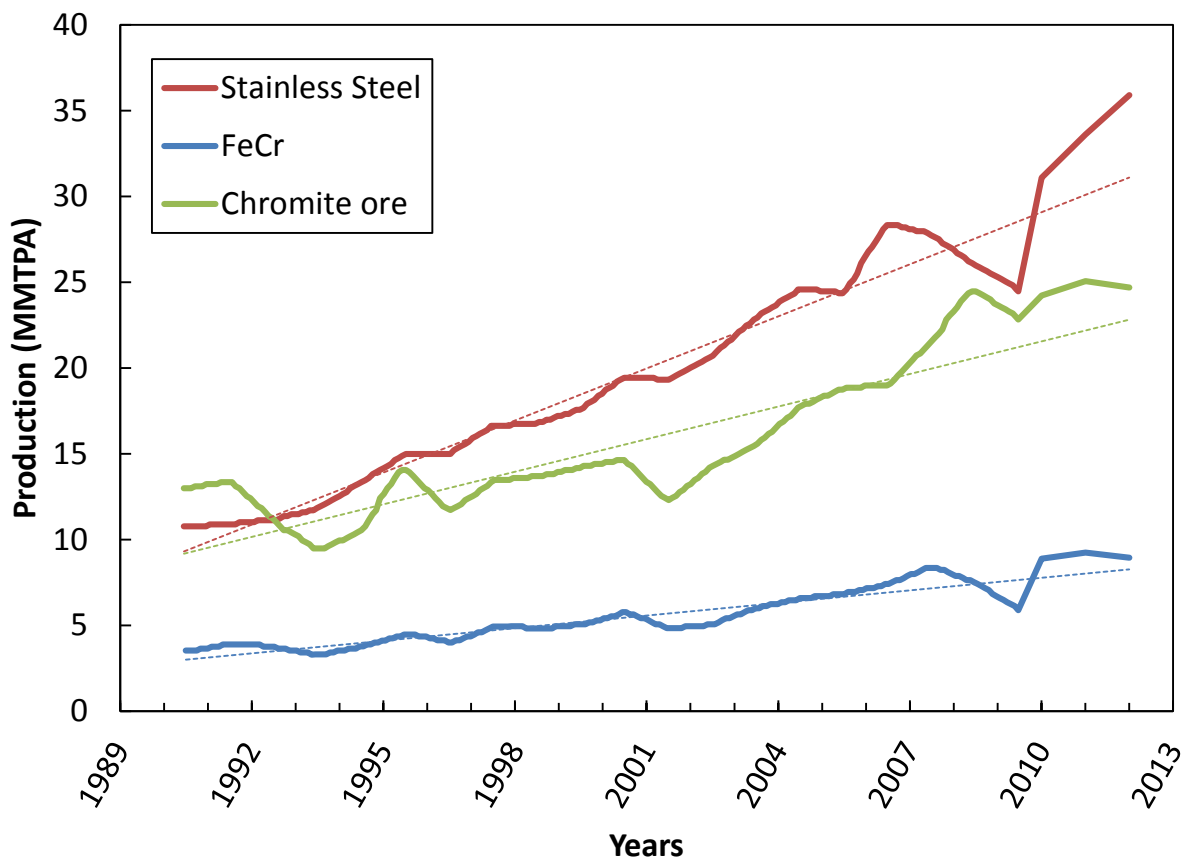


Figure 2-4: World production in million metric tons per annum (MMTPA) for 1990-2012 (Anon, 2010b; ICDA, 2013d)

FeCr prices are usually negotiated every quarter by South African producers for European and Asian consumers, irrespective of the volume and tenure of the contracts as depicted in the chart above. This price is a benchmark for all other contracts including spot market contracts, barring a few instances. Depending on the demand-supply situation at the time, the movement of spot prices is generally in tandem with quarterly contractual prices. The benchmark South African contracts are priced as US cents/lb of Cr content (Ideas 1st Research, 2010). Historically, it is observed that the prices of chromite ore, FeCr, and chromite ore move in tandem. Figure 2-5 indicates the correlation between the chromite ore price and the stainless steel and FeCr price indexes. Long term contracts in the stainless steel market are priced in two parts namely base value and alloy surcharge. Normally base values are kept constant for the duration of the contract, while the alloy surcharge prices are revised on a recurring basis to compensate for the volatility in the alloy mix. The alloy surcharge price is decided by the major components in

stainless steel. They are chromium, nickel, molybdenum and manganese. The price fluctuation of nickel influences the grade production of stainless steel, as 60% of the total stainless steel produced contains nickel while the balance 40% has a very low nickel content (Ideas 1st Research, 2010). The expansions of both the Chinese and Indian economies were thought to be the main influences for the increase in Cr prices from 2007 through to part of 2008. The global financial meltdown in the late 2008 caused the prices to dramatically decline (Papp, 2008).

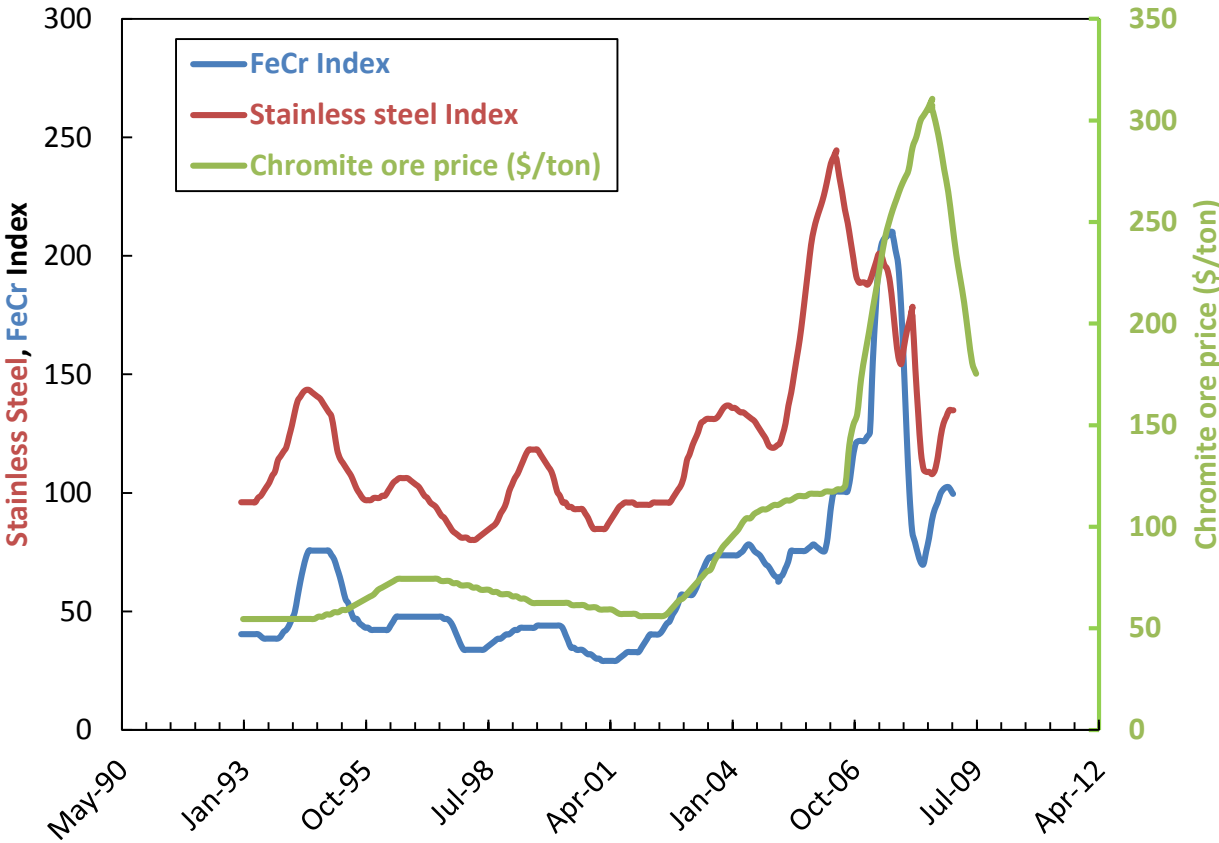


Figure 2-5: Chromite ore price (\$/ton) and the stainless steel (SS) and FeCr price indexes (Anon, 2010a; Anon, 2010b)

The South African Rand exchange rate is a potentially significant factor in the price of chromite ore and FeCr because RSA is a leading producer of these materials (Papp, 2008). RSA is also the largest and second largest exporter of platinum and gold respectively, thus it is expected that these two markets would have a significant influence on RSA’s currency (Anon, 2010b). Figure 2-6 shows the monthly average South African Rand (ZAR) per U.S. Dollar (US\$) exchange rate in comparison with the historical FeCr prices (ZAR/kg) (Anon, 2011b). From these exchange rate fluctuations the volatility and possible financial effect on the South African FeCr industry are evident.

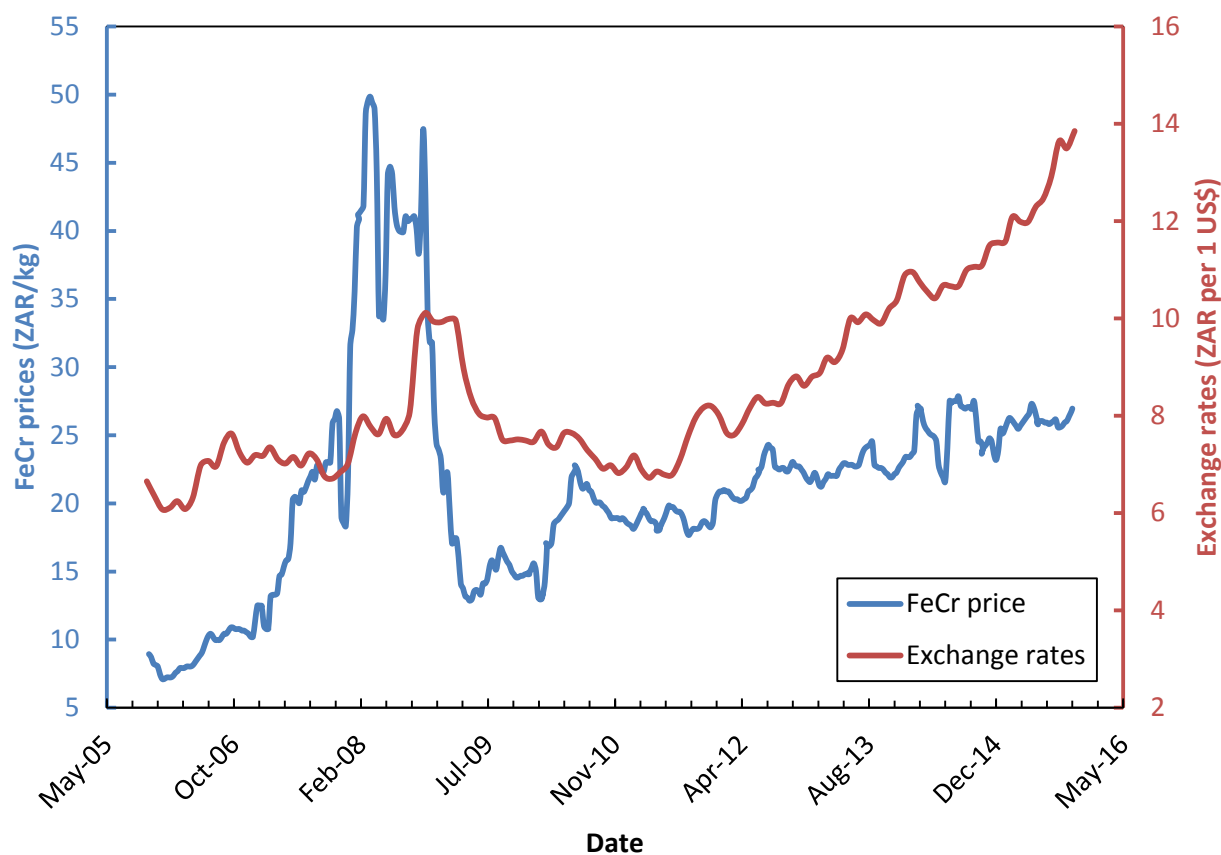


Figure 2-6: Monthly average exchange rates: South African Rand (ZAR) per U.S. Dollar (US\$) and the FeCr price (ZAR/kg) (Anon, 2011b)

2.1.3 Carbonaceous Reductants

Another factor that has a significant impact on the South African FeCr industry is the availability of suitable reductants. Anthracite, char and coke are the main carbon reductants used (Makhoba & Hurman Eric, 2010). For FeCr production a reductant with a low ash, low phosphorus and low sulphur content is required (Basson *et al.*, 2007; Anon, 2010b; Makhoba & Hurman Eric, 2010). Due to the specific properties required, reductant availability is a cause of concern for FeCr producers. Moreover, there is no regulation within reductant markets and therefore over-supply or shortages may occur regularly resulting in enormous price fluctuations. In addition, the steel industry has a major influence on the dynamics of coking coal prices (Anon, 2010b; Makhoba & Hurman Eric, 2010). Typical properties of reductants for ferro alloy production are presented in Table 2-2 (Basson *et al.*, 2007).

Table 2–2: Typical properties of selected carbon reductants used in ferro alloy production (Basson *et al.*, 2007)

Characteristic	Anthracite	Char/Gas coke	Coal	Chinese charge grade FeCr coke	SA charge grade FeCr coke
Volatile %	6-10	1-2	18-25	< 1	< 1
Ash %	15	19	11	14	16
Fixed carbon %	80	80	56	85	83
Sulphur %	0.6	0.2	0.8	0.6	0.7
Phosphorus %	0.004	0.009	0.009	0.013	0.009

Around 50-60% of coking coal requirement in RSA over the past years were met through long-term contracts but were reset to an on spot basis. Low ash and phosphorous grade coking coal come with premiums, which makes price negotiations for FeCr producers difficult. With this in mind it is clear that coking coal prices will have an impact on FeCr production and prices in the near future (Ideas 1st Research, 2010).

RSA has enough resources and has been self-sufficient for many years with respect to reductants for ferro alloy production (Basson *et al.*, 2007, Ideas 1st Research, 2010). Substantial coal reserves are located in five major basins and recoverable coal and anthracite materials were estimated to be around 61 000 Mt (Barcza *et al.*, 1982, Featherstone & Barcza, 1982). In recent years it has however become necessary to import reductants for alloy production. Metallurgical coke is mostly imported from China for FeCr production and Zimbabwe for manganese alloy production. The rapid increase in RSA's ferro alloy production capacity along with no growth in coke production capacity in recent years is the main reason for importation. The trend towards closed furnaces, mostly for environmental reasons, generally require a larger fraction of coke in the reductant mixture, which also contributed to coke shortages (Basson *et al.*, 2007, Ideas 1st Research, 2010). Specific coke and char consumption for charge grade FeCr production has increased by 0.2 tonnes over the last few years at the expense of coal. Ferro alloy producers are also looking to increase the usage of anthracite in ferroalloy production. Anthracite has mainly been applied in DC charge grade FeCr furnaces and smaller AC charge

grade FeCr and manganese alloy furnaces. For economic reasons the usage of metallurgical coal is maximised within the constraints that are experienced with the use of coal on larger, closed furnaces. The number 1, 2 lower and 5 coal seams in the Witbank basin are currently the primary source of metallurgical coal. It has a sulphur and phosphorous content of 0.7 and 0.012% respectively (Basson *et al.*, 2007).

With respect to reductants, there are two challenges the South African FeCr industry are facing at the moment. From the facts mentioned in the previous paragraph it can be concluded that the first problem is that producers are importing coke because of a lack in local coke production capacity. The second problem is supply constraints of low phosphorus and sulphur coals for use as such or for conversion of these coals into coke, gas coke and char. As far as the former is concerned, Mittal Coke and Chemical expanded their coke capacity to 450 000 t/a primarily for FeCr and ferromanganese production in RSA. There were also indications of coke production from other major players. As far as the latter is concerned, it is believed that deposits of metallurgical grade coal that belonged to big mining companies that did not exploit these resources will be allocated to small black economical empowered (BEE) entrepreneurs because of the Mineral and Petroleum Resource development Act (Act 28 of 2008). This small scale mining of coal resources would make reductants available to the ferro alloy industry instead of being lost to steam coal exports and feedstock to power stations. Over the next 15 years the existing coalfields will be depleted and production of coal will shift to the vast Waterberg reserves located in the Northern Province. Thus, as far as the foreseeable future, RSA will have enough carbon reductants at its disposal (Basson *et al.*, 2007).

2.1.4 Electricity supply

The electricity demand of RSA has caught up with its electricity generating capacity (Baker, 2006). The historic supply-demand overview of electricity in RSA up to 2014 is shown in Figure 2–7 (Pfister, 2006; Basson *et al.*, 2007). From this it is clear that the availability of surplus generation capacity has significantly been eroded. By 2007, Eskom had run out of electricity and couldn't meet the rising demands any more. The erosion of surplus generation capacity has led to a dramatic increase in electricity prices, indicated in Figure 2–8, that is set to continue in the foreseeable future (Basson *et al.*, 2007). In the period 1980 to 2005 the nominal electricity price in RSA increased steadily at a rate of roughly 0.58 RSA cents/kWh per

year (Anon, 2009b). According to statistics from the National Energy Regulator of South Africa (NERSA), the nominal price of electricity increased by 174% from 2007 to 2010 (Anon, 2009a; Anon, 2009b). NERSA subsequently granted Eskom a three-year rate increase resulting in electricity costs of 41.57 RSA cents/kWh for 2010/11, 52.30 RSA cents/kWh for 2011/12 and 65.85 RSA cents/kWh for 2012/13 (Anon, 2009a; Anon, 2011a). NERSA since allowed Eskom to raise tariffs by an average 8% for 5 years (2014-2018), however, recently they approved an annual average price increase of 12.69% for 2015/16, which is made up of the 8% annual price increase approved in the original MYPD 3 decision and an additional 4.69% as allowed through the revenue clearing account (RCA) mechanism which forms part of the NERSA regulatory methodology. Considering that electricity consumption is the single largest cost component in FeCr production (Daavittila *et al.*, 2004), the afore-mentioned cost increases are extremely significant. However, the pressure on South African FeCr producers is not unique, since globally lower SEC (MWh/t FeCr) and a decreased carbon footprint have become driving factors.

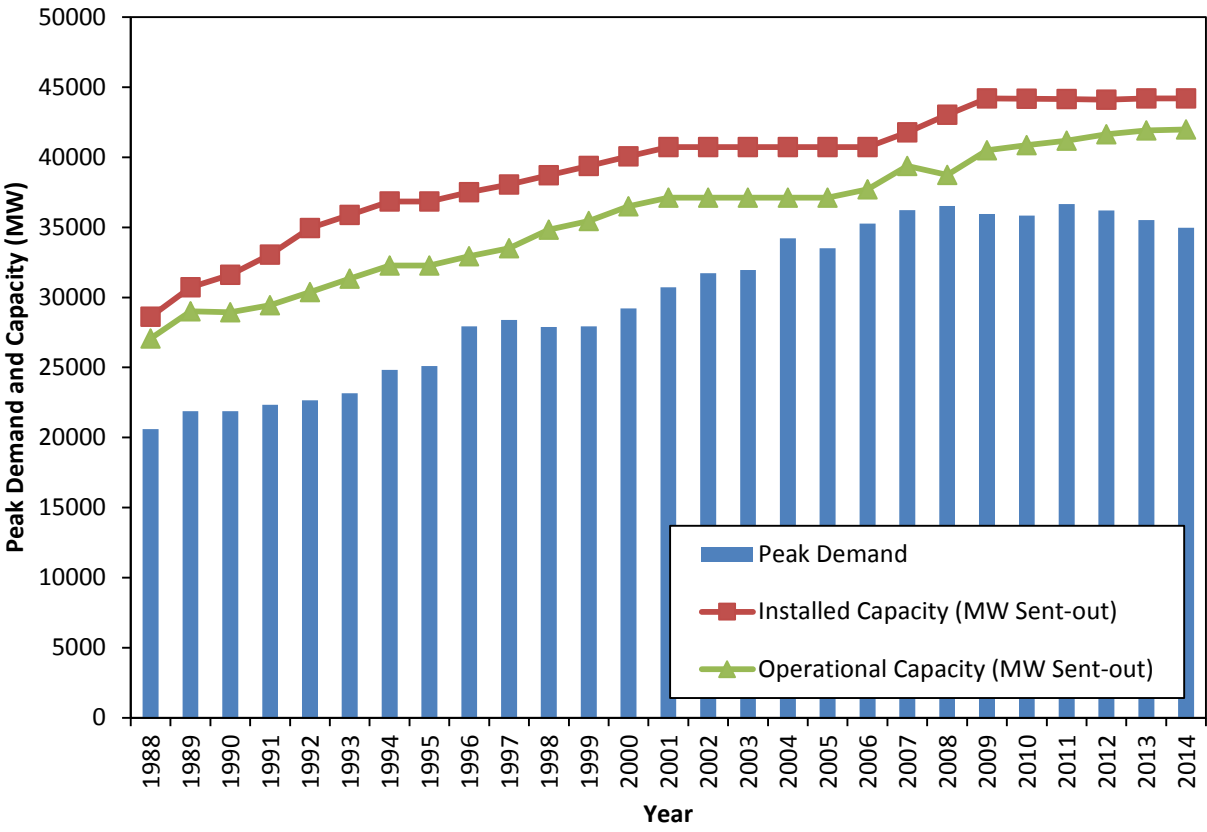


Figure 2-7: Electricity demand overview for South Africa (Pfister, 2006; Basson et al., 2007)

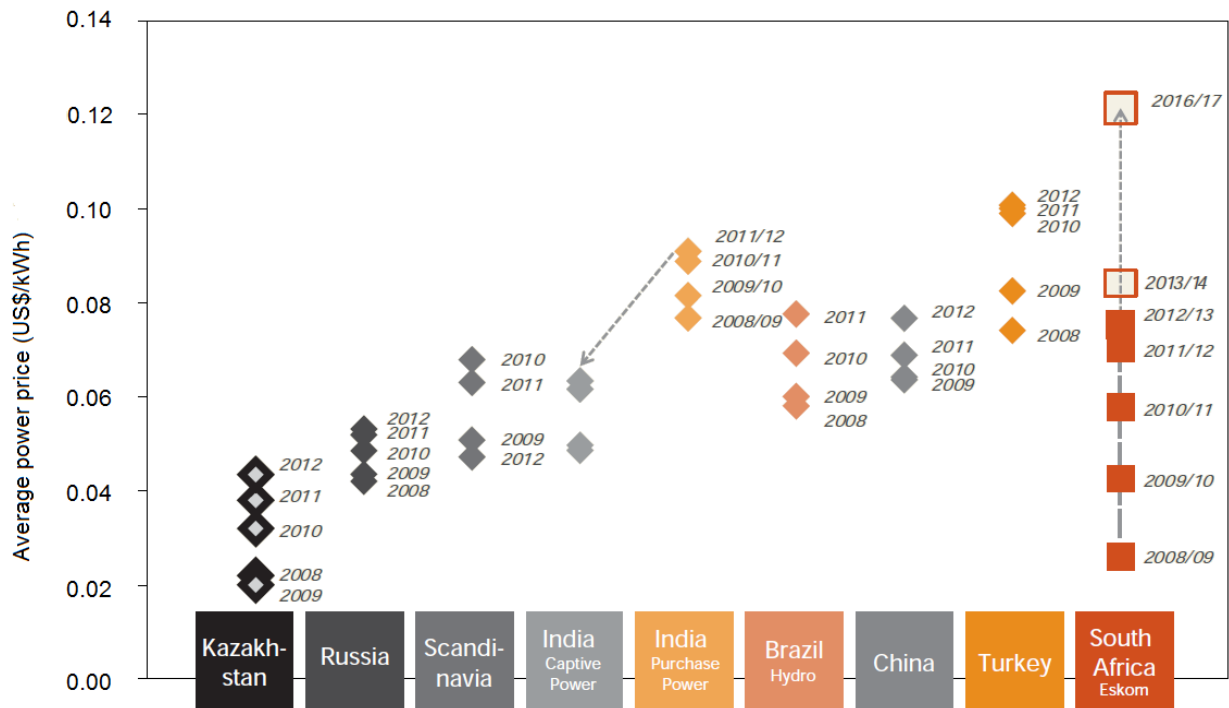


Figure 2–8: Comparison of electricity prices in selected countries (All data based on average power prices and exchange rates for the years stated. South African projection based on 2012 exchange rate.)

2.1.5 Ferrochrome production

The advent of argon-oxygen decarburisation 50 years ago triggered the expansion of RSA’s FeCr industry, which led to RSA becoming the world leader in FeCr production (Featherstone & Barcza, 1982; Basson *et al.*, 2007). This can be ascribed to an abundance of good quality raw materials (ore, reductants and fluxes), historically relatively low electricity costs, adequate infrastructure and reasonably low-cost capital (Basson *et al.*, 2007). In 2009 RSA produced around 2.3 million metric tonnes of the world’s charge grade FeCr, the most common production grade. This was 38.92% of the 5.9 million metric tonnes produced world-wide. When considering statistics of the International Chromium Development Association (ICDA) Statistical Bulletin 2013, depicted in Figure 2–9, it is evident that RSA’s charge grade FeCr production went down by 7.37% from 46.29% in 2007 to 38.92% in 2009. This can be ascribed to the world economic crisis, as well as the situation surrounding RSA’s electricity supply mentioned previously. Consequently RSA, the largest producer of FeCr for the last decade, with ~30% of global production in 2012, was overtaken by China who doubled their production in the last 3 years, filling the rapid growing demand for FeCr of the SS industry (ISSF, 2011; ICDA,

2013c). China increased its FeCr production with about 1 million tonnes extra capacity between 2013 and 2014 (ICDA, 2013c). The summarised production capacities of RSA's FeCr smelter plants are shown in Table 2–3 (Basson *et al.*, 2007; Bonga, 2009; Jones, 2010; Beukes *et al.*, 2012).

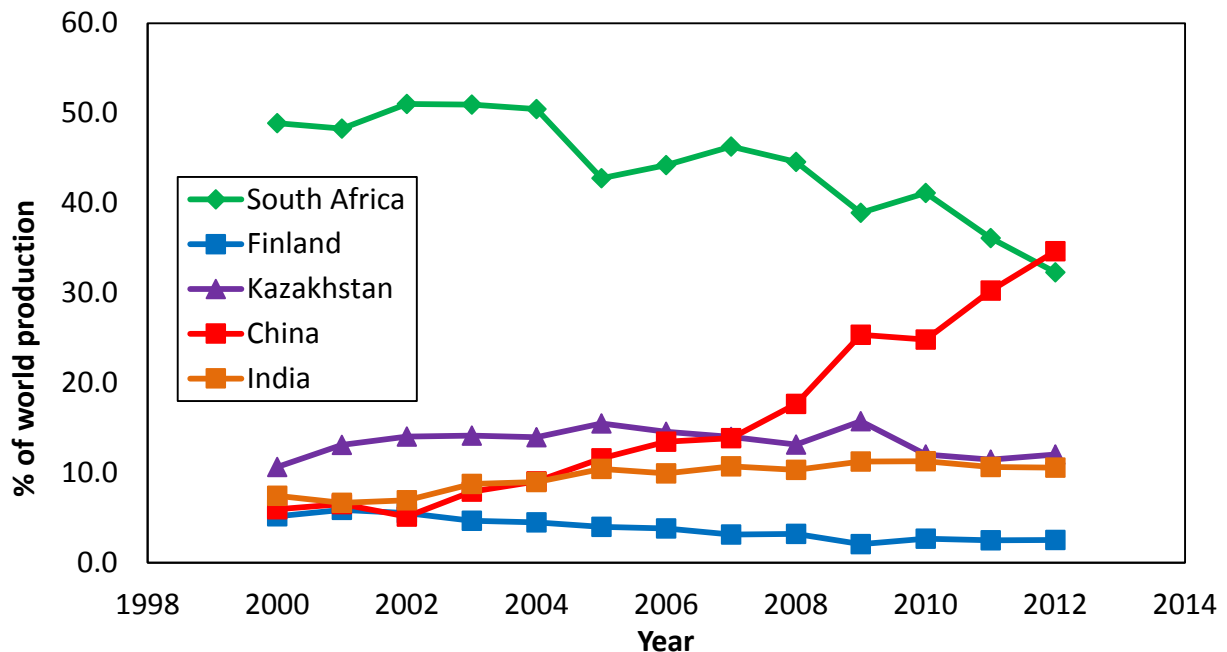


Figure 2–9: High-carbon charge grade FeCr production 2000-2014 (Anon, 2010c; ICDA, 2013d)

Table 2–3: Production capacity of South African FeCr producers adapted from Jones (2015)

Plant	Locality	Production capacity (t/a)
ASA Metals Dilokong	Burgersfort	400 000
Assmang Chrome	Machadodorp	300 000
Ferrometals	Witbank	550 000
Hernic Ferrochrome	Brits	420 000
International Ferro-Metals	Rustenburg-Brits	267 000
Middelburg Ferrochrome	Middelburg	285 000
Mogale Alloys	Krugersdorp	130 000
Tata Ferrochrome	Richards Bay	135 000
Tubatse Ferrochrome	Steelpoort	380 000
Glencore Alloys Lydenburg	Lydenburg	400 000
Glencore Alloys Boshhoek	Rustenburg-Sun City	240 000
Glencore Alloys Lion	Steelpoort	720 000
Glencore Alloys Rustenburg	Rustenburg	430 000
Glencore Alloys Wonderkop	Rustenburg-Brits	545 000
TOTAL		~5 202 000

2.2 Main processes and techniques

2.2.1 Mining and beneficiation of chromite ores

Open-cast mining as well as underground mining techniques are used to obtain raw chromite ore. Specific mining techniques vary widely depending on the local resources and materials (Nafziger, 1982; Gediga & Russ, 2007).

The purpose of beneficiation is to render the ore physically (granulometry) and chemically suitable for subsequent treatments. Operations typically serve to separate and concentrate mineral values from waste materials, remove the impurities or prepare the ore for further refinement. Beneficiation activities do not change the mineral values themselves other than by reducing (crushing and grinding) or enlarging (pelletising and briquetting) particle size to facilitate further processes. Chromite ore is beneficiated for processing using several methods. The ore source, end use sector requirements, mineral characteristics of the ore deposits, gangue mineral assemblage and the degree of dissemination of constituent minerals determine the beneficiation practices and methods that are used. A general representation of a chromite ore beneficiation process is shown in Figure 2–10 and consists of two sections, i.e. comminution (preparing the material for subsequent unit operations) and concentration (Abubakre *et al.*, 2007; Murthy *et al.*, 2011).

In the feed preparation section the run-of-mine ore is screened from ± 220 mm to 75 mm. This is followed by a primary and secondary crushing stage separated by screening to produce an offset of less than 3 mm. The secondary crushers offset is recycled back and rescreened. The crushed ore is then further grounded to less than 1 mm. In the concentration section the ore is upgraded using conventional gravity techniques, e.g. spiral concentrators (Murthy *et al.*, 2011).

Though gravity techniques are well established and widely accepted for the concentration of chromite ore, such techniques become inefficient and complex while treating very fine size particles of less than 75 μm . Recovery is a concern particularly in finely disseminated ores due to its inherent complexities. Each gravity separation technique delivers its maximum efficiency under specific operating conditions and particle size range (Murthy *et al.*, 2011).

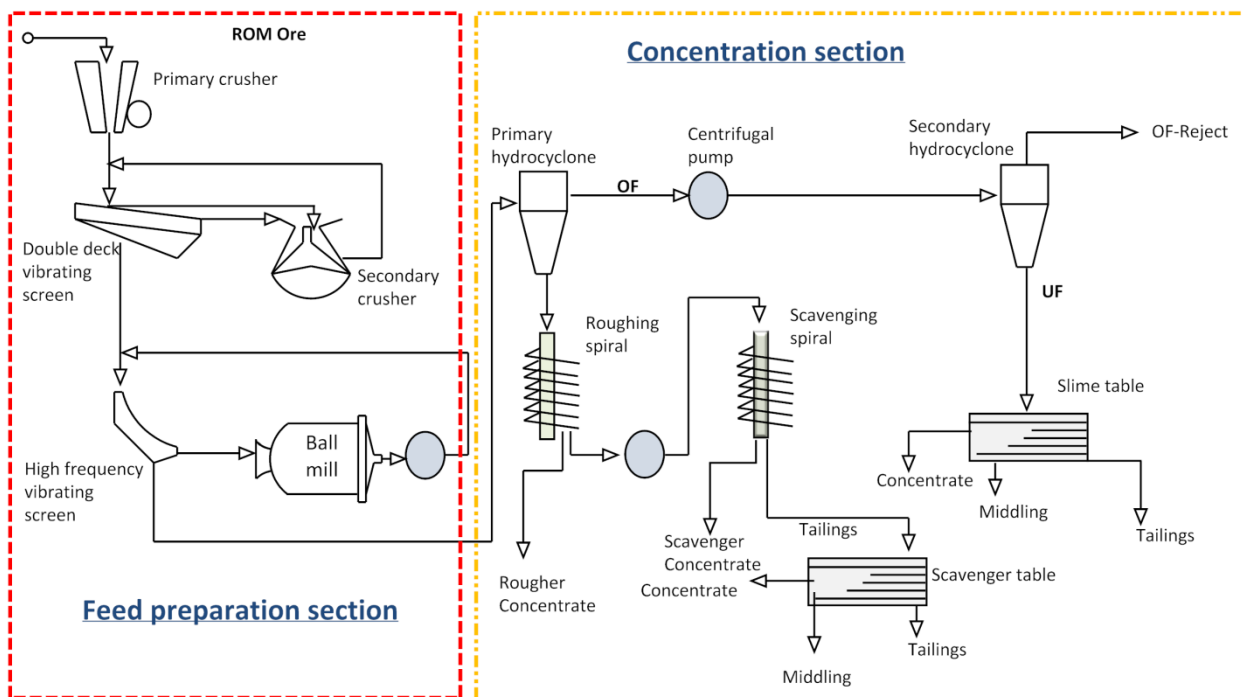


Figure 2–10: General process flow sheet for chromite ore beneficiation (Murthy *et al.*, 2011)

Heavy medium and gravity concentration methods are the most commonly used beneficiation processes. Heavy medium separation is the most economical method when coarse particles ranging between 10 to 100 mm need to be treated. In the case of finer particles, jigs, spirals and shaking tables are used. Spirals are, however, the most important among gravity concentrators and are currently the preferred choice. Cr can be recovered within the range of 80 to 85% when using these processes (Howat, 1986; Gu & Wills, 1988).

Gravity separation methods predominate over flotation techniques (Nafziger, 1982). Flotation is thus not a major method of beneficiation for chromite ores. In some instances fatty acids, such as oleic acid, have been used where flotation has been adopted as a method of separation. Chromite ores from different locations exhibit a wide variation in surface properties which is a major difficulty when making use of flotation (Gu & Wills, 1988).

All chromite ores are paramagnetic at room temperature. Their magnetic capacity is dependent on the Fe^{2+} content (Owada & Harada, 1985). It has been speculated that this ferromagnetism is predominantly present in the sections more concentrated with Fe^{2+} because of the non-uniform distribution of magnetic ions in the crystalline structure. Low-intensity magnetic separation (about 0.1 T) is used to reject the magnetite from paramagnetic chromite material, but is inefficient in separating the chromite ores that are present in fine intergrowths

with other materials. In a high-intensity magnetic field (about 1 T) chromite can be extracted as a magnetic product from the gangue material (Nafziger, 1982; Gu & Wills, 1988).

South African chromite ores are relatively friable and easily break down to the size of the chromite crystals (Gu & Wills, 1988). Due to this friability, it is common to only recover 10 to 15% lumpy ore (15 mm < typical size range < 150 mm) and 8 to 12% chip or pebble ores (6 mm < typical size range < 15 mm) during the beneficiation process employed after chromite mining. The remaining ore would typically be in the < 6 mm fraction, which would usually be crushed and/or milled to < 1 mm and then upgraded utilising typical gravity separation techniques (e.g. spiral concentrators) to approximately 45% Cr₂O₃ content. This upgraded < 1 mm ore is commonly known as metallurgical grade chromite ore (Glastonbury *et al.*, 2010).

2.2.2 Ferrochrome production processes

A generalised process flow diagram, which indicates the most common process steps utilised by South African FeCr producers, is shown in Figure 2–11 (Beukes *et al.*, 2010).

In general, four relatively well-defined process combinations are utilised by South African FeCr producers (Beukes *et al.*, 2010):

A) **Conventional open or semi-closed SAF operations, with bag filter off-gas treatment.**

This is the oldest technology applied in RSA, but still accounts for a substantial fraction of overall production (Gediga & Russ, 2007). In this type of operation, coarse (lumpy and chips/pebble ores) and a small fraction of fine ores can be smelted without an agglomeration process undertaken to increase the size of fine ores. Although it has been stated that fine ores cannot be fed directly into a SAF without causing dangerous blow-outs or bed turnovers (Riekkola-Vanhanen, 1999), fine ores are in fact fed into some semi-closed furnaces in the South African FeCr industry. With reference to the process flow diagram indicated in Figure 2–11, the process steps followed are 5, 7, 8, 9 and 10. Some semi-closed furnaces do consume pelletized feed, in which case process steps 1-4 would also be included. Most of semi-closed furnaces used in RSA are operated on an acid slag, with a basicity factor smaller than 1. Equation 2–1 defines the basicity factor (BF) (Beukes *et al.*, 2010):

$$BF = \frac{\%CaO + \%MgO}{\%SiO_2}$$

2-1

Some semi-closed furnaces might operate on $BF > 1$, but these are less common and such operations are sometimes only temporarily undertaken to compensate for refractory linings being in poor condition, or if enhanced sulphur removing capacity by the slag is required (Beukes *et al.*, 2010).

- B) **Closed furnace operation, usually utilising an oxidative sintered pelletised feed (Outotec, 2015).** This has been the technology most commonly employed in RSA, with the majority of green and brown field expansions utilising this combination of process steps during the last decade. Process steps usually include steps 1, 2, 3, 4, 5, 7, 8, 9 and 11, with or without 6. In all green field FeCr developments the pelletising and sintering (steps 2 and 3) sections were combined with closed furnaces. However, pelletising and sintering sections have also been constructed at plants where the pelletised feed is utilised by conventional semi-closed furnaces. These furnaces are usually operated on an acid slag ($BF < 1$) (Beukes *et al.*, 2010).
- C) **Closed furnace operation with pre-reduced pelletised feed (Botha, 2003; Naiker, 2007).** The process steps include steps 1, 2, 3, 4, 5, 7, 8, 9, 11. The pelletised feed differs substantially from the oxidative sintered type due to the fact that the pellets are pre-reduced and mostly fed hot, directly after pre-reduction, into the furnaces. The furnaces are closed and operate on a basic slag ($BF > 1$). At present, two South African FeCr smelter plants use this process.
- D) **DCF operation (Denton *et al.*, 2004; Curr, 2009).** For this type of operation, the feed can consist exclusively of fine material. Currently three such furnaces are in routine commercial operation for FeCr production in SA and typically utilize a basic slag regime ($BF > 1$). Process steps include 5, 7 (with a DC, instead of a SAF), 8, 9 and 11. Drying (process step 6) might also be included.

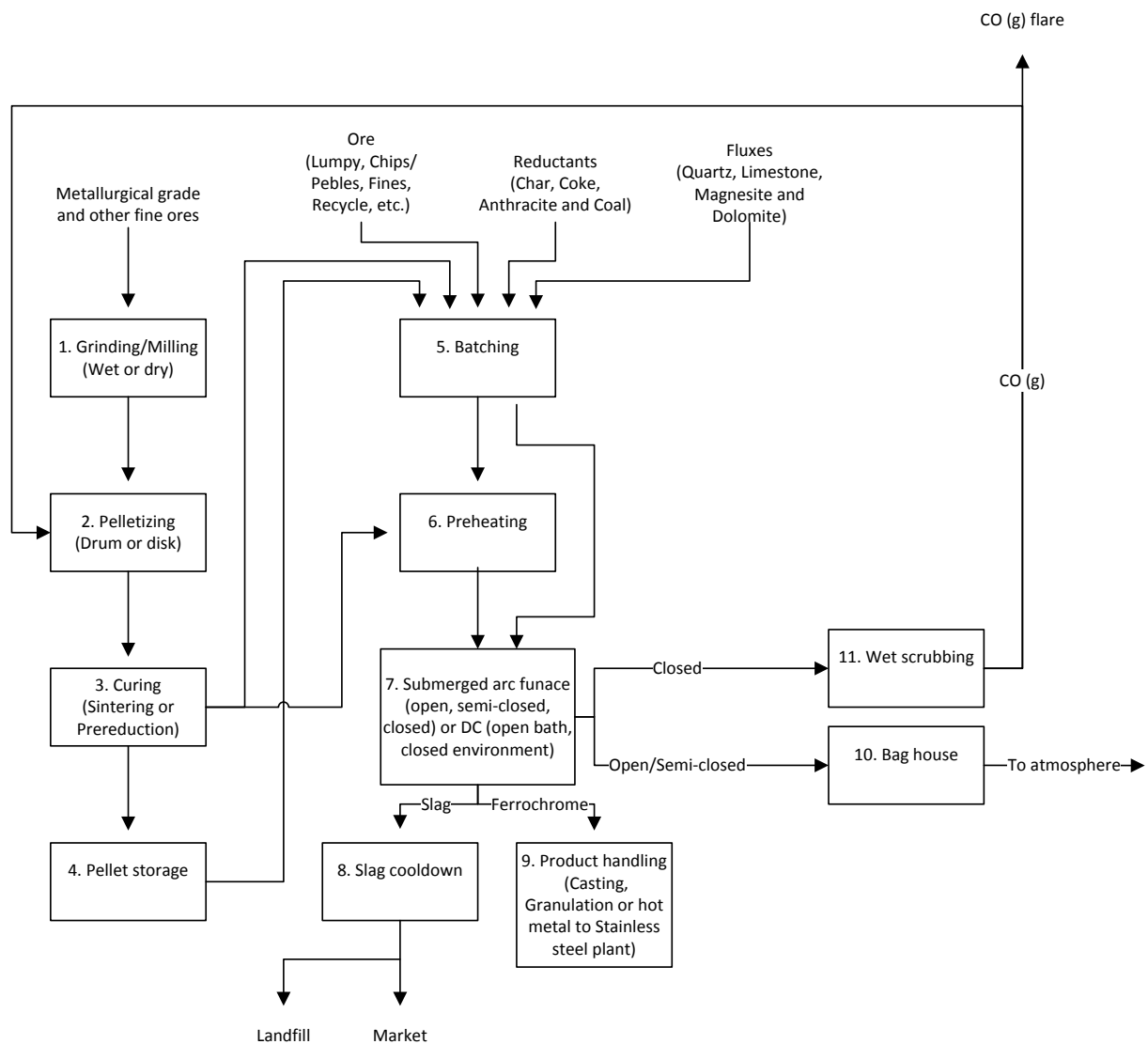


Figure 2–11: A flow diagram adapted by Beukes *et al.* (2010) from Riekkola-Vanhanen (1999), indicating the most common process steps utilised for FeCr production in South Africa

2.3 Chromite pre-reduction

2.3.1 Extent of pre-reduction technology commercialisation

Pre-reduction technology has been around for a number of years, with the pre-reduction of Fe ore being a more commonly utilised process. Remarkably, pre-reduction of chromite has not been widely used on a commercial scale; however, it is a very well-established practice in RSA and has been utilised since 1975 (Dawson & Edwards, 1986; Basson *et al.*, 2007; Naiker, 2007; McCullough *et al.*, 2010). It is currently the second most commonly employed technology in the South African FeCr industry (Beukes *et al.*, 2010). A number of studies have been

conducted on the pre-reduction of chromite ore utilising different reductant sources including coke, anthracite, carbon monoxide, methane and hydrogen. This has led to a few processes being partially developed as well as implemented on a commercial scale.

The solid-state reduction of chromite (SRC) process developed by Showa Denko in Japan was the first commercially successful process (Naiker, 2007). In this process, Cr ore fines are milled in a ball mill, pelletised using a clay binder with coke added as reductant, dried in a travelling grate kiln, and fired in a rotary kiln to approximately 1400 °C. The kiln is heated by a burner using pulverised coal, CO or oil as fuel (Riekkola-Vanhanen, 1999). The SRC process has been employed with success at two commercial facilities, i.e. the Shunan Denko Plant in Japan and the Consolidated Metallurgical Industries (CMI) Plant in Mpumalanga, RSA. These two facilities have proved to be the most energy efficient FeCr production plants (Naiker, 2007). When Xstrata purchased the CMI plant in 1998 from the Johannesburg Consolidated Industries (JCI) group, they wanted to decrease cost structures at the Lydenburg plant. Therefore, between 1998 and 2001, they developed the Premus process, based on the SRC process, mainly by in-plant trials. Xstrata made a fundamental change in the operating philosophy of the process in that the Premus process sought to maximize the energy output from the kiln while still achieving the required efficiencies and therefore increasing furnace output, while the original CMI process's main objective was to maximize metallisation in the pellets (Naiker, 2007). In 2006 third quarter Xstrata increased their FeCr capacity with the commissioning of its Lion FeCr smelter plant which also makes use of a pre-reduction stage utilising Xstrata's Premus technology (Basson *et al.*, 2007; McCullough *et al.*, 2010). In 2010 Xstrata announced the seconded phase expansion of the Lion plant that involved the construction of another 360 000 t/y capacity smelter, raising their total FeCr production capacity above 2.3 million t/y (Creamer, 2010; Wait, 2011).

Alternative processes that have been used or have been partly developed include the Krupp-Codir CDR (Chromium Direct Reduction Process) and Rotary Hearth Furnace (RHF) that was later acquired by Polysius, as well as Outokumpu's pre-treatment process (McCullough *et al.*, 2010).

The CDR process uses unagglomerated ore fines. Self-agglomeration of the fines occurs inside the rotary kiln in the high temperature zone. A temperature of approximately 1500 °C is used and the kiln feed consists of chromite concentrate, a siliceous flux, and a large excess of

reductant. Coal is used as both energy source and reductant (Dawson & Edwards, 1986; Riekkola-Vanhanen, 1999). A big disadvantage of this process is that the excess reductant must be separated from the metal-slag mixture before smelting can commence. To achieve this, the kiln discharge must be cooled which results in a substantial loss of enthalpy (Dawson & Edwards, 1986). SAMANCOR installed the CDR pre-reduction process at its Middelburg FeCr Plant with the process involving the partial fluxing of Cr ore fines (not pellets) and the use of oxygen enrichment to attain temperatures of around 1500 °C, but ran into problems in particular with damring build-up (material sticking to the inside of the rotary kiln) and refractory wear.

INMETCO developed its Direct Reduced Iron (DRI) Technology process utilizing a RHF and applied it with great success to stainless steel dust recycling. However, attempts to apply the RHF process to Cr ore pre-reduction were only partly successful, the main problem being the re-oxidation of the pre-reduced Cr pellets (McCullough *et al.*, 2010). Tenova Pyromet in co-operation with its technical partners, Paul Wurth and Tenova LOI Italimpianti, has recently developed a pre-reduction process for FeCr ores based on using Rotary Hearth Furnace technology fired with closed furnace off-gas, but the process has not yet been industrially applied (Dos Santos, 2010).

Outokumpu studied its process for about ten years in the laboratory and on pilot scale as well as for two years in a commercial scale operation. The process consisted of a rotary kiln with a length of 55 m and inner diameter of 2.3 m. The major problem that they encountered was to maintain an even pre-reduction degree. Consequently, the furnace operations became difficult to maintain and efficiency were not good enough to make the operation viable, so they returned to using the equipment for preheating (Daavittila *et al.*, 2004).

2.3.2 Strategic advantages of chromite pre-reduction

Although various processes are utilised in the production of FeCr, the use of pelletised pre-reduction chromite has a number of key advantages over other processes:

- a) Pre-reduction's most important advantage is certainly the reduction of the overall process electric energy consumption. At present, high-carbon/charge grade FeCr is generally produced in electric arc furnaces. A major disadvantage of this process is

the amount of electrical energy required for the reduction of the metal oxides to the metallic state. In order to minimize energy consumption and consequently improve cost efficiency, solid-state carbothermic pre-reduction of chromite has become a necessary option, since it requires the lowest SEC for operation of all FeCr production processes (Weber & Eric, 2006; Neizel, 2010). With pre-reduction levels of up to 90% for the Fe and 50% achieved for Cr, electrical energy consumption is reduced by approximately 40% from around 3.9 MWh/t required in conventional ore fed processes down to 2.4 MWh/t (McCullough *et al.*, 2010). The net SEC as a function of the degree of chromite pre-reduction achieved and then charged into an arc furnace at different temperatures was reconstructed from Takano *et al.* (2007) and Niayesh and Fletcher (1986) and is presented in Figure 2–12.

- b) The process utilises 100% fine chromite ore, therefore taking maximum advantage of friable chromite ore available in RSA (Naiker & Riley, 2006).
- c) Providing an agglomerate feed to furnaces thus reducing the risk of bed turnovers and blowouts occurring (Naiker & Riley, 2006).
- d) Although pre-reduction capital cost is higher than the capital incurred for a conventional process, it is still the lowest capital cost per annualised ton of FeCr (Naiker, 2007).
- e) High recoveries of metallic oxides (90%).
- f) Production of a low silicon product (< 3%).
- g) The use of lower cost fine reductants instead of lumpy reductants and the use of oxygen as an energy source (Botha, 2003; Naiker & Riley, 2006; Naiker, 2007).

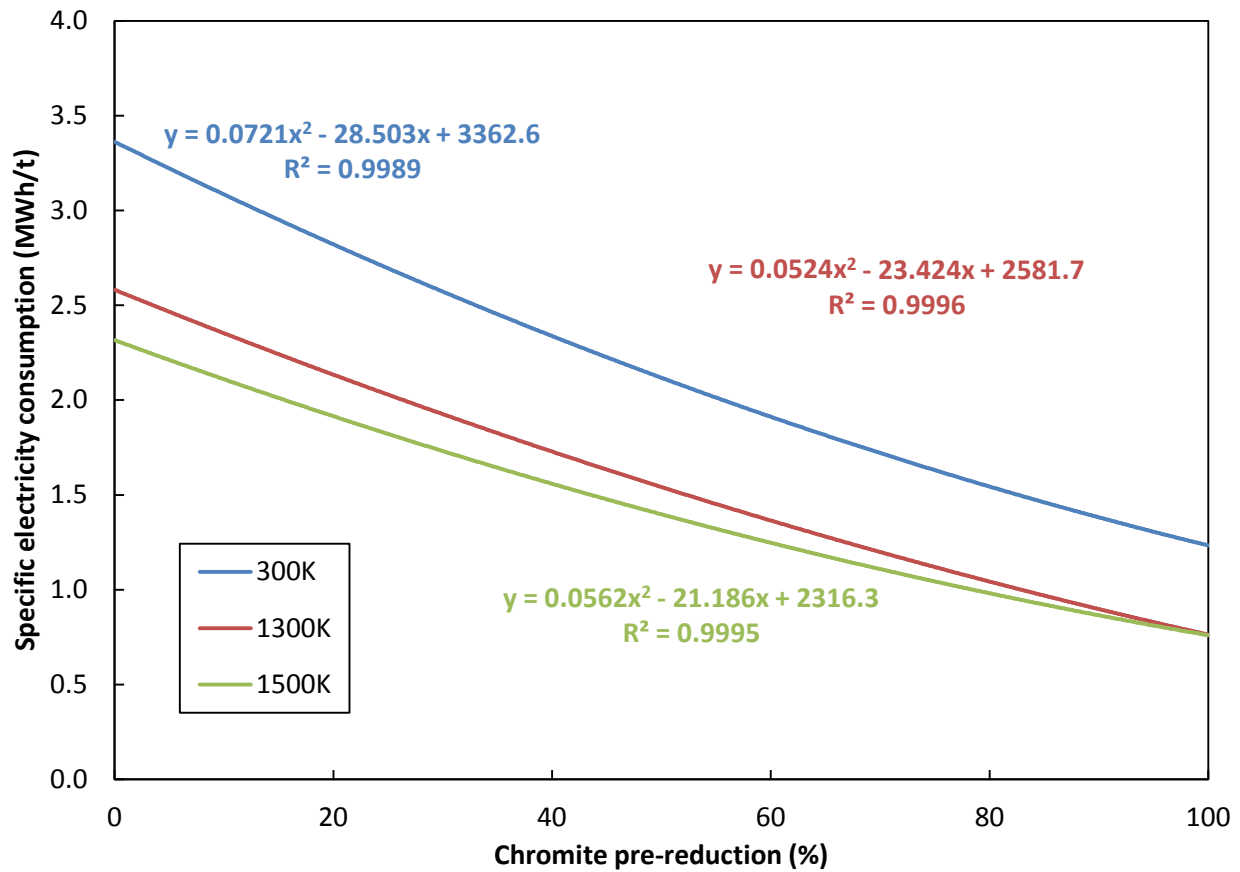


Figure 2–12: Net energy requirement for the production of 1 ton of FeCr as a function of the degree of pre-reduction achieved and charging temperature (Niayesh & Fletcher, 1986; Takano et al., 2007)

2.3.3 Fundamental aspects of chromite pre-reduction

In a chromite pre-reduction process certain terms are used to describe the reduction rate and extent of reduction and metallisation. It is therefore necessary to define these terms before going into further discussions. Barnes *et al.* (1983) proposed definitions for the terms “degree of reduction” and “metallisation” which have since been used by some researchers (Soykan *et al.*, 1991a; Weber & Eric, 2006). Given that the removal of oxygen is associated with reduction, the extent of reduction, R(%), was defined as (Barnes *et al.*, 1983):

$$R(\%) = \frac{\text{Mass of oxygen removed}}{\text{Original removable oxygen}} \times 100 \quad 2-2$$

In the pre-reduction process solid carbon is used as a reductant and CO is thus formed as a reduction reactions product (illustrated in Equation 2–5, Equation 2–6 and Equation 2–7), with 1 mole of CO forming for 1 mole of oxygen removed from the ore oxides. The extent of reduction can thus also be defined as (Barnes *et al.*, 1983):

$$R(\%) = \frac{\text{Mass of CO evolved}}{28/16 \times \text{Original removable oxygen}} \times 100 \quad 2-3$$

The amount of removable oxygen used to define Equation 2–2 and Equation 2–3 is determined from the oxygen loss associated with the metal oxides Fe₂O₃, FeO and Cr₂O₃.

The extent of metallisation, M(%), is defined as (Barnes *et al.*, 1983):

$$M(\%) = \frac{(\text{Cr}^0 + \text{Fe}^0)}{(\text{Cr}_{\text{tot}} + \text{Fe}_{\text{tot}})} \times 100 \quad 2-4$$

Where: Cr⁰ is the amount of Cr reduced to the metal state
 Fe⁰ is the amount of Fe reduced to the metal state
 Cr_{tot} is the total Cr amount
 Fe_{tot} is the total Fe amount

Since complete oxygen removal corresponds to complete metallisation, 100% reduction corresponds to 100% metallisation. The relationship between metallisation and reduction is, however, not linear and Barnes *et al.* (1983) attributed this to the following factors:

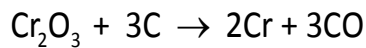
- 1) In the early stages of reduction, Fe₂O₃ is reduced to FeO without any metallisation:



- 2) FeO is reduced to Fe⁰, producing 1 mol of CO for every mole of Fe⁰ produced:



3) Cr_2O_3 is reduced to Cr^0 , producing 1.5 mol of CO per mole of Cr produced:



2-7

Dawson and Edwards (1986) illustrated the individual difference in metallisation and reduction of Fe and Cr, confirming the above mentioned factors proposed by Barnes *et al.* (1983). A graphic illustration of this relationship between reduction and metallisation were reconstructed for Dawson and Edwards (1986) and shown in Figure 2-13.

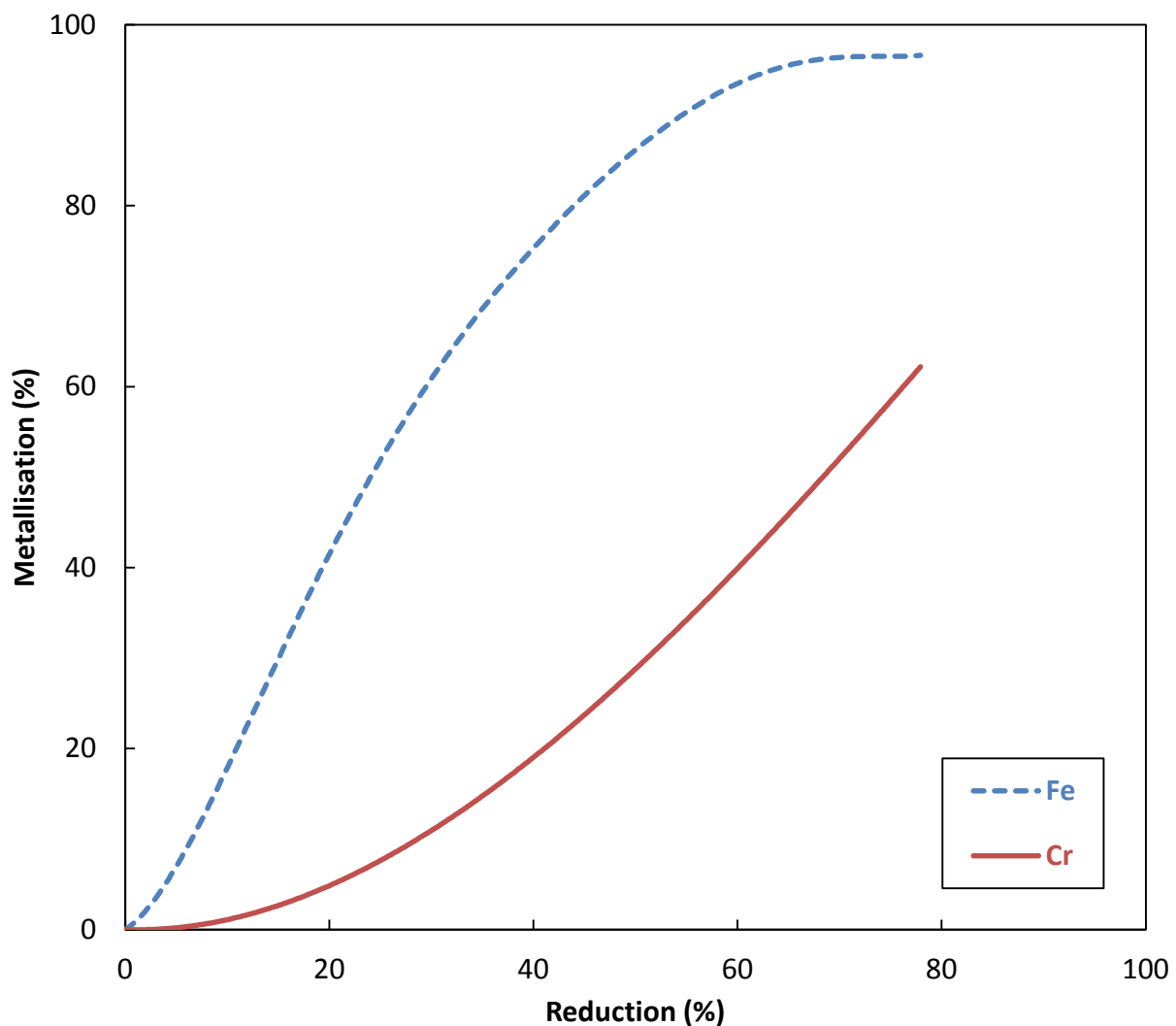


Figure 2-13: The relationship between reduction and metallisation, based on South African LG-6 chromite treated at 1200 °C (Dawson & Edwards, 1986)

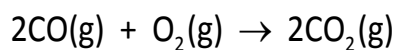
Chromite ore is primarily composed of $\text{FeO}\cdot\text{Cr}_2\text{O}_3$, $\text{MgO}\cdot\text{Cr}_2\text{O}_3$, $\text{MgO}\cdot\text{Al}_2\text{O}_3$, $(\text{Cr,Al})_2\text{O}_3$, forming a complex spinel structure and may also hold a certain amount of free Fe, not contained inside the spinel (Takano *et al.*, 2007). The general formula for South African chromite ore located in

the BIC is $(\text{Fe}_{0.74}^{2+} \text{Mg}_{0.27})_{\Sigma=1.01} (\text{Cr}_{1.42} \text{Al}_{0.40} \text{Fe}_{0.15}^{3+} \text{Ti}_{0.01} \text{V}_{0.01})_{\Sigma=1.99} \text{O}_4$. The reduction mechanism for chromite is therefore much more complex, due to the number of metal oxides, slag components (SiO_2 , TiO_2 , Al_2O_3 , MgO , CaO , including gaseous Mg and SiO) and alkalis contained inside the spinel structure or existing as free compounds (Niemelä *et al.*, 2004).

Takano *et al.* (2007) identified three ways in which high temperature reduction of chromite using a carbon reductant can generally occur, i.e. i) solid chromite is reduced by solid or gaseous reductant; ii) direct reaction at the interface between the slag and metal, where the dissolved chromite in the slag are reduced by carbon dissolved in the metal phase; and iii) direct reaction between dissolved chromite in the slag and the carbon particles floating on it. In SAF mechanisms ii and iii should be predominant, while in the chromite pre-reduction process a large portion of chromite is expected to reduce by solid or gaseous reductants before liquid phase formation. The reduction of oxides is based on solid carbon and carbon monoxide gas. The reduction reactions are indicated in Equation 2–8 and Equation 2–9 (Niemelä *et al.*, 2004).



2-9



Niemelä *et al.* (2004) investigated the formation, characterisation and utilisation of CO-gas formed during the carbothermic reduction of chromite. According to the Ellingham diagram calculations the authors conducted (indicated in Figure 2–14) they showed that solid carbon reduces Fe_2O_3 to FeO at around 250 °C. The reduction of Fe_3O_4 to FeO occurs kinetically at temperatures above approximately 710 °C. FeO is reduced to the Fe^0 state at relatively low temperatures, around 710 °C and above, while the reduction of Cr_2O_3 occurs at higher temperatures of 1250 °C and above. Carbon monoxide reduces Fe_2O_3 to Fe_3O_4 over the whole calculated temperature range, but as mentioned earlier reduction of Fe_3O_4 to FeO occurs kinetically above 710 °C. From the calculations it is evident that the reduction of Cr_2O_3 and ($\text{FeO}\cdot\text{Cr}_2\text{O}_3$) is not possible with carbon monoxide alone.

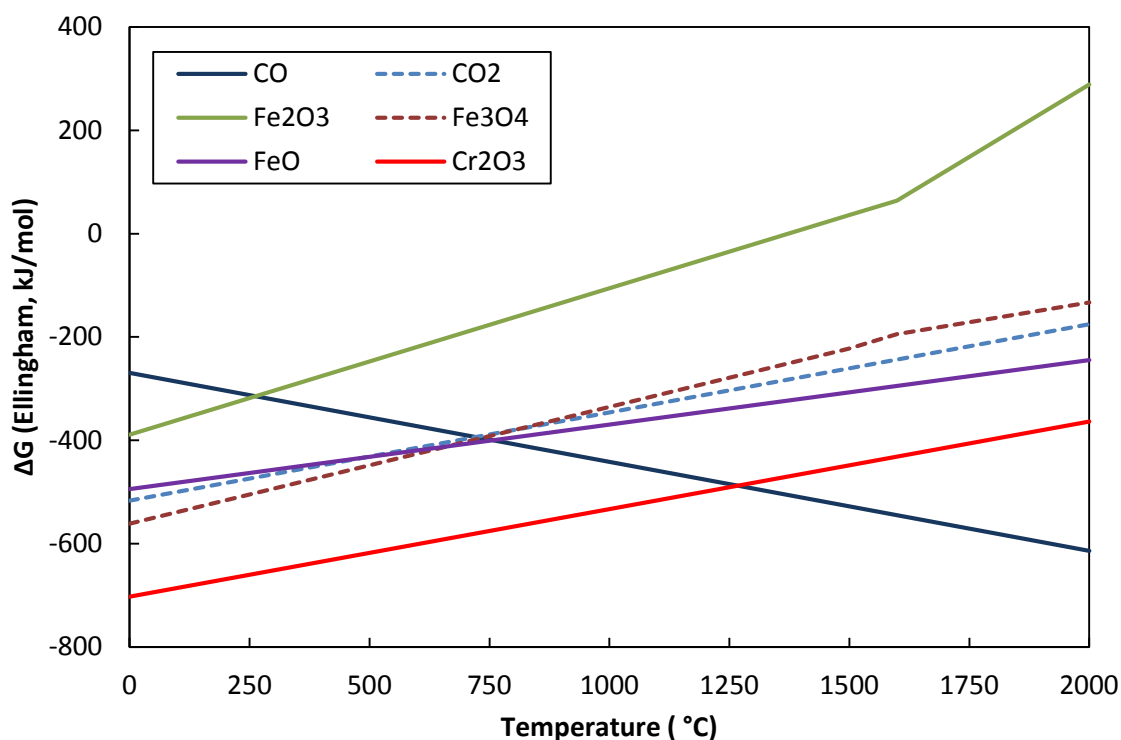


Figure 2–14: Standard free energies of reduction of metal oxides with carbon and carbon monoxide (Niemelä et al., 2004)

The mechanisms and kinetics of the reduction of South African chromite ores have been studied by numerous researchers. A comprehensive reference list of these investigations is given by Hayes (2004). Significant results on the solid-state carbothermic reduction mechanism and kinetics of a chromite from the LG6 layer of the BIC treated at 1400 °C have been published by Soykan *et al.* (Soykan *et al.*, 1991a; Soykan *et al.*, 1991b). Soykan *et al.* proposed a stoichiometric ionic diffuse reduction model involving somewhat complex reactions among the solid carbon reductant, altered chromite spinel phases, and various ionic species. It also included site-exchange mechanisms between Fe^{2+} and Cr^{3+} ions, with the Cr^{3+} being placed in octahedral sites due to its very high affinity for octahedral coordination (Soykan *et al.*, 1991a; Soykan *et al.*, 1991b; Weber & Eric, 1993; Weber & Eric, 2006). The proposed mechanism, furthermore, included a swap mechanism between the Cr^{2+} ions of the surface unit cell and the Fe^{2+} ions of the unit cell just below the surface. Soykan *et al.* (1991a&b) observed that localisation occurred in partially reduced chromite and that all the oxygen are removed from the surface as Fe and Cr is reduced. The inner cores were found to be rich in Fe, whereas the outer cores were depleted of Fe. A graphic representation, shown in Figure 2–15, of the reduction of chromite was proposed by Ding & Warner (1997b) correlating to the observations of Soykan *et al.* (1991a&b). Soykan *et al.* (1991a&b) revealed that, within the outer core

(Reduced area, Figure 2–15), Fe^{2+} and Cr^{3+} ions diffused outward, whereas Cr^{2+} , Al^{3+} and Mg^{2+} ions diffused inward. Initially, Fe^{3+} and Fe^{2+} ions at the surface of chromite particle (Interface 1, Figure 2–15) were reduced to the metal state. This was followed immediately by the reduction of Cr^{3+} ions to the 2+ oxidation state. Cr^{2+} ions diffusing toward the inner core of the particle reduced the Fe^{3+} ions in the spinel under the surface of the particle to Fe^{2+} at the interface (Reduced area, Figure 2–15) between the inner and outer cores. Fe^{2+} ions diffuse toward the surface, where they were reduced to metallic Fe. After the Fe had been completely reduced, Cr^{3+} and any Cr^{2+} that was present were reduced to the metal state, leaving a Fe and Cr free spinel, MgAl_2O_4 . The metallised Fe and Cr carburised during the reduction into $(\text{Fe,Cr})_7\text{C}_3$ according to Equation 2–10 and Equation 2–11.



2-11

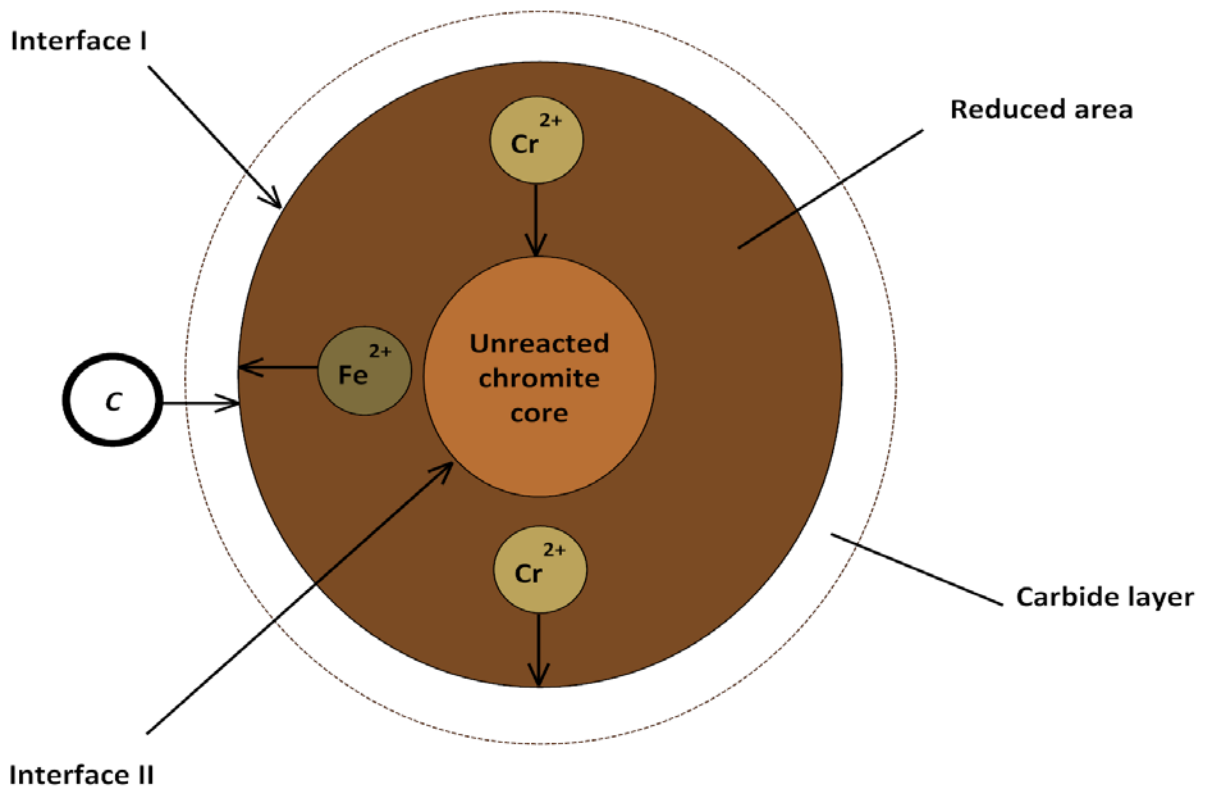
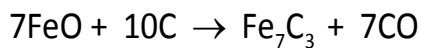


Figure 2–15: Schematic representation of the reduction mechanism of chromite (Ding & Warner, 1997b)

CHAPTER 3: BACKGROUND ON PRE-OXIDATION FUNDAMENTALS

In this chapter, information on the fundamental aspects of the pre-oxidation process is provided. The effect of pre-oxidation temperature on pre-reduction (Section 3.2), surface chemical and microstructural effects caused by pre-oxidation (Section 3.3) and the effect of pre-oxidation on the crystalline structure of chromite (Section 3.4) are presented. In Section 3.5, theoretical thermochemical considerations surrounding pre-oxidation are discussed. Section 3.6 deals with the implications that alterations to process pre-reduction levels has on energy consumption. The effect of pre-oxidation on the mechanical strength as well as thermomechanical behaviour of pre-reduction pellets is provided in Section 3.7 and 3.8, respectively. Finally, Section 3.9 offers information on the formation of Cr(VI) during chromite pre-oxidation.

3.1 Introduction

Although the focus of this dissertation is on the techno-economic feasibility of integrating chromite pre-oxidation into the pre-reduction process, limited information on the pre-oxidation process currently exists in public domain (patent in progress and publication accepted). Therefore this chapter is an extension of the literature survey, but specifically focusses on the pre-oxidation prior to milling agglomeration and pre-reduction process. This will enable the reader to better understand the techno-economic study that is presented in the results chapter, i.e. Chapter 4.

3.2 Effect of pre-oxidation temperature on pre-reduction

The effect of the pre-oxidation of fine chromite ore, prior to being milled, pelletised and pre-reduced, on the level of chromite pre-reduction achieved was report on by Kleynhans *et al.* (2015) and is illustrated in Figure 3–1. The base case, when un-oxidised chromite ore is utilised, is indicated by the red horizontal dotted line. It is clear that pre-oxidation between 800 to 1100 °C improves the level of chromite pre-reduction, with pre-oxidation at 1000 °C being the optimum pre-oxidation temperature to maximise the level of achievable pre-reduction. It is

important to note that pre-reduction levels start to decline with pre-oxidation temperatures above 1000 °C. At pre-oxidation temperatures higher than 1200 °C, pre-reduction levels achieved are even lower than the base case utilising un-oxidised ore.

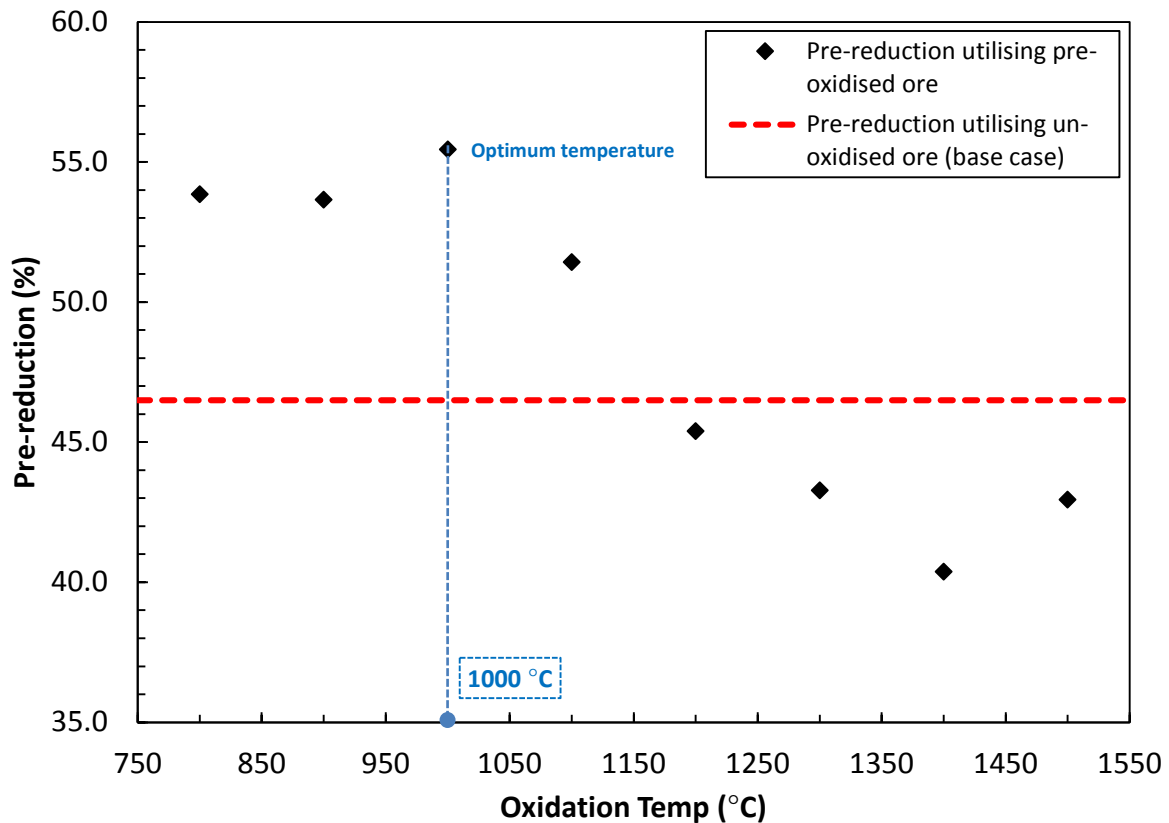


Figure 3–1: The effect of pre-oxidation temperature of fine chromite ore, prior to milling, agglomeration and pre-reduction, on the extent of chromite pre-reduction (adapted from Kleynhans *et al.* (2015)).

From an operational FeCr production perspective, the results presented in Figure 3–1 are very promising. Firstly, the SEC and lumpy carbonaceous materials required for smelting in the SAF will be lower with improved pre-reduction. Secondly, the highest pre-oxidation temperatures did not correlate with the best pre-reduction levels. This is encouraging from a production cost perspective, since lower pre-oxidation temperatures imply lower operational costs.

It is somewhat unexpected that the highest pre-oxidation temperatures did not result in the highest pre-reduction levels achieved (Kleynhans *et al.*, 2015), since the general preconceived assumption is that higher pre-oxidation temperatures would result in a more significant alteration of the very stable chromite spinel, which could result in achieving higher pre-reduction levels (Zhao & Hayes, 2010). Since this was not the case, it was important to

understand why this trend occurred, to ensure that optimum process conditions can be maintained during operation. In the subsequent sections (Sections 3.3 to 3.5), various findings and conclusions made by Kleynhans *et al.* (2015) are discussed in order to assist in understanding or explaining observations in Figure 3–1.

The effect of pre-oxidation on pre-reduction pellet strength, which will also be discussed (Section 3.7), is an equally important operational parameter since excessive formation of fines in the furnace feed materials could have disastrous consequences (Riekkola-Vanhanen, 1999; Beukes *et al.*, 2010).

Hexavalent Cr or Cr(VI) can be formed in many of the existing FeCr-production steps (Beukes *et al.*, 2010). Cr(VI) is generally considered as carcinogenic, mutagenic, and teratogenic, although there seems to be inadequate evidence to support the carcinogenicity of all Cr(VI) compounds. Possible Cr(VI) generation during the pre-oxidation process was investigated by Kleynhans *et al.* (2015) and therefore also discussed in Section 3.9, as it is vital to consider possible occupational health and environmental aspects during process development.

3.3 Surface chemical and microstructural effects caused by pre-oxidation

SEM back-scatter micrographs and X-ray map images reported on by Kleynhans *et al.* (2015) of chromite ore particles, specifically un-oxidised ore, as well as pre-oxidised ore at 1000 °C and 1400 °C, are shown in Figure 3–2. The two pre-oxidation temperatures, 1000 °C and 1400 °C, represents the best and worst case pre-reduction scenarios in addition to the un-oxidised ore (base case).

Figure 3–2A and Figure 3–2B shows a SEM micrograph and an X-ray map of the un-treated ore, respectively. From the SEM micrograph (Figure 3–2A) it is apparent that the un-oxidised chromite ore particles had relatively clean or smooth surfaces with relatively sharp edges. The X-ray map of the polished un-oxidised ore particles (Figure 3–2B) indicate that all elements (i.e. Cr, Fe, Si) were homogeneously spread throughout the chromite particles with no indication of elemental migration or the presents of enrichment zones.

The SEM micrograph of chromite ore pre-oxidised at 1000 °C (Figure 3–2C) indicates that a crust formed on the surface of the chromite ore particles. The accompanying X-ray map (Figure 3–2D) shows the occurrences of some Fe (depicted with the colour red) enrichment areas on

the surface of the ore particles. From these images, Kleynhans *et al.* (2015) concluded that Fe migration to the surface of the ore particles had occurred to some extent, due to pre-oxidation of the ore at 1000 °C.

Kleynhans *et al.* (2015) expected that this Fe migration associated with pre-oxidation would be further enhanced at higher pre-oxidation temperatures. This was confirmed by the SEM micrograph (Figure 3–2E) and X-ray map (Figure 3–2F) of the chromite ore pre-oxidised at 1400 °C. From Figure 3–2E, it is evident that the crust formed on the outside of the chromite ore particles become more significant with an increase in pre-oxidation temperature. The accompanying X-ray map (Figure 3–2F) also illustrates a very clear Fe-enriched area on the surface of the chromite particles. Additionally, the silica (Si indicated in blue in Figure 3–2F) in the gangue minerals seems to have melted at this higher pre-oxidation temperature. However, this observation is not relevant to the particular discussion and will not be elaborated on further. It is evident from Figure 3–2 that Fe migration to the surface of the chromite ore particles was enhanced by increasing the pre-oxidation temperature. According to the Ellingham diagram presented by Niemelä *et al.* (2004) (Figure 2–14), it is apparent that, thermodynamically, solid elemental C can reduce higher oxidation states of Fe, i.e. Fe₂O₃ and Fe₃O₄, to FeO at relatively low temperatures, while FeO is reduced to the metal state (Fe⁰) above ~710 °C. In contrast, Cr₂O₃ reduction requires much higher temperatures, i.e. ≥1250 °C. Kleynhans *et al.* (2015) therefore noted that should the SEM and X-ray map results be considered in isolation, an increase in the chromite pre-reduction levels is expected, due to enhanced Fe-oxide migration from the spinel to the ore particle surface when the pre-oxidation temperature is raised. However, this was not the case (Figure 3–1). Therefore, Kleynhans *et al.* (2015) performed XRD analysis on the same samples (un-oxidised ore, as well as ore pre-oxidised at 1000 and 1400 °C) in order to find possible explanations for the observed decrease in pre-reduction of ores pre-oxidised at 1400 °C. XRD analysis provides information on the crystalline content of samples, which may well remain undetected with SEM and X-ray map analyses.

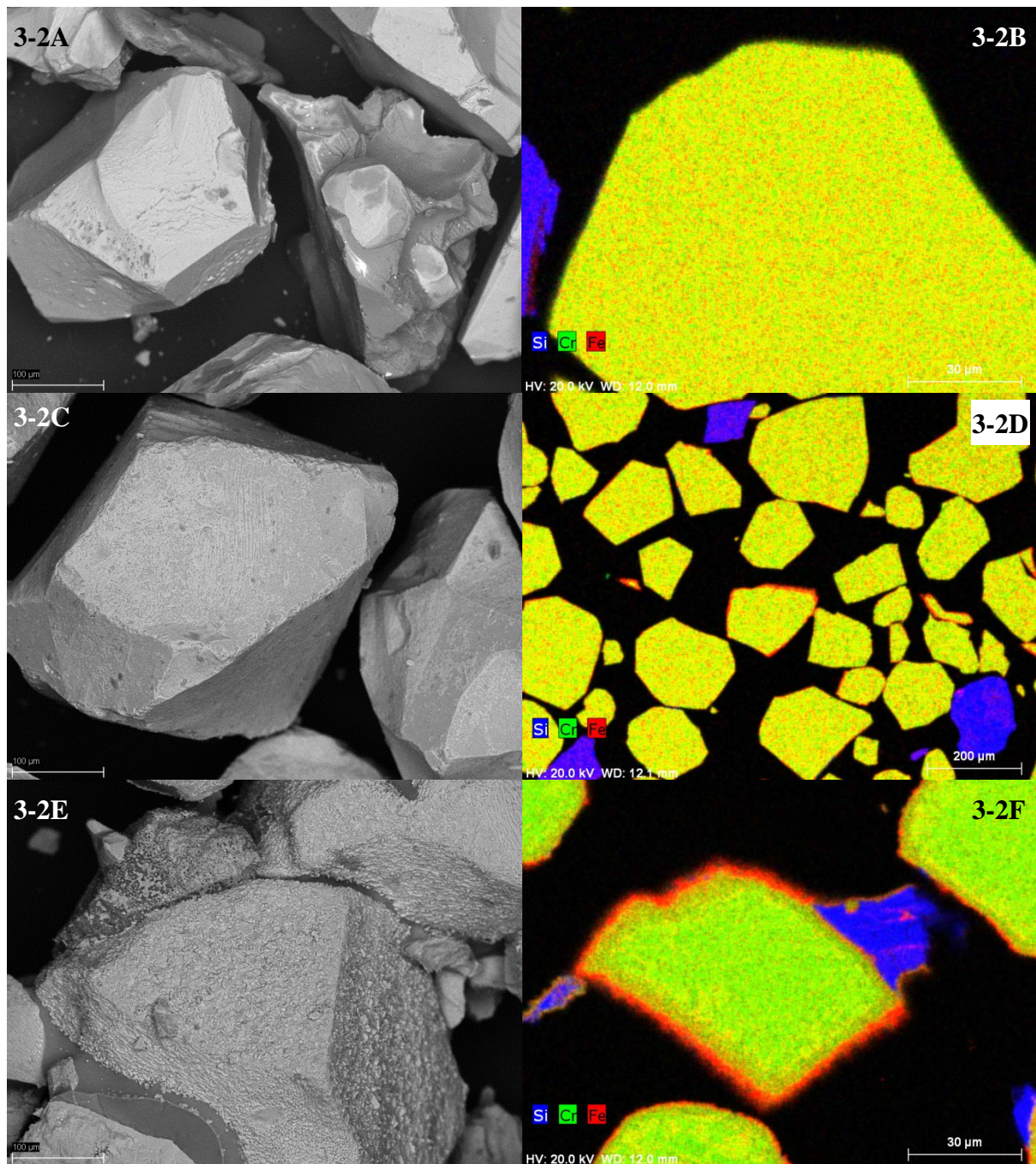


Figure 3–2: SEM back-scatter micrographs and X-ray maps by Kleynhans *et al.* (2015) illustrating the effect of pre-oxidation temperature of fine chromite ore, prior to milling, agglomeration and pre-reduction, on the extent of chromite pre-reduction, i.e. un-oxidised ore (A and B), ore pre-oxidised at 1000 °C (C and D) and ore pre-oxidised at 1400 °C (E and F).

3.4 Effect of pre-oxidation on the crystalline structure of chromite

In Figure 3–3A, B and C, XRD spectra obtained by Kleynhans *et al.* (2015) of un-oxidised chromite ore, as well as chromite ore pre-oxidised at 1000 °C and 1400 °C are presented, respectively. Figure 3–3D presents the peak list providing information used to identify compounds in these XRD spectra.

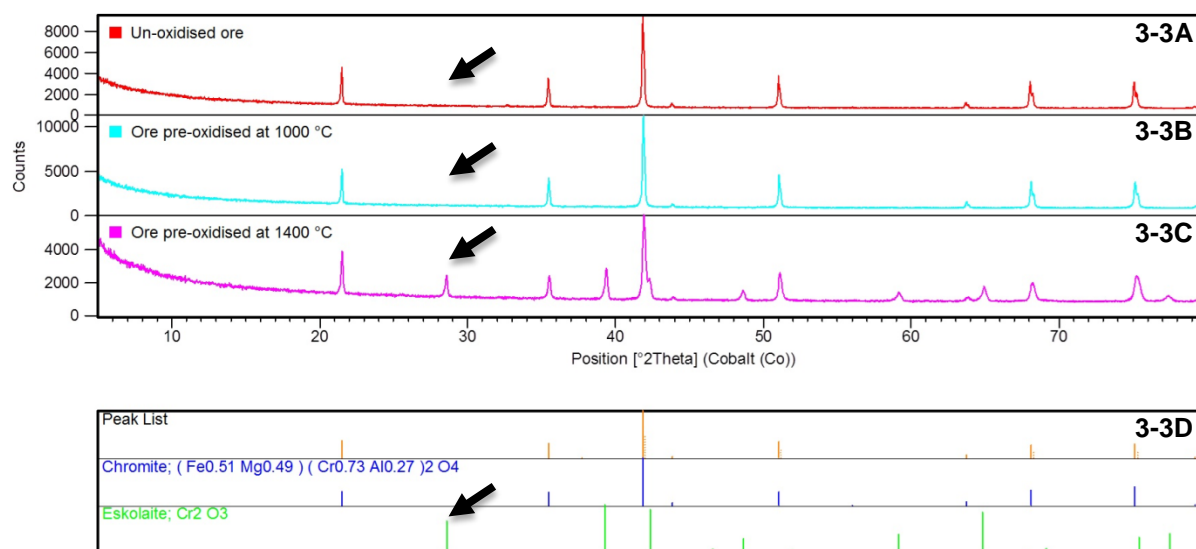


Figure 3–3: XRD spectra of un-oxidised chromite ore (A), chromite ore pre-oxidised at 1000 °C (B) and chromite ore pre-oxidised at 1400 °C (C). The peak list (D) provide information used to identify peaks observed in the above-mentioned XRD spectra. The arrows indicate one of the peaks used as an indicator of the absence/presence of eskolaite (Cr_2O_3) in the materials. (Spectra taken from Kleynhans *et al.* (2015))

Kleynhans *et al.* (2015) identified that the X-ray diffraction patterns of the un-oxidised chromite ore (Figure 3–3A) and chromite ore pre-oxidised at 1000 °C (Figure 3–3B) are the same, notwithstanding the small amount of Fe that migrated to the surface of the chromite particles, as indicated in Figure 3–2 by means of X-ray map analysis. Kleynhans *et al.* (2015) attributed this to Fe oxides being particularly difficult to detect with XRD analysis at low concentrations, due to their poor crystallinity (small crystal size and structural disorder) and unspecific particle shape, which requires the use of Fe-specific methods, such as Mössbauer spectroscopy for determination (Schwertmann, 2008). It is therefore not surprising that the XRD spectra of the un-oxidised chromite ore and chromite ore pre-oxidised at 1000 °C were the same. However, for the chromite ore pre-oxidised at 1400 °C (Figure 3–3C), Kleynhans *et al.* (2015) pointed out that additional peaks had formed in the XRD spectrum. According to the XRD peak list of

standard materials (Figure 3–3D), these additional peaks correlated with eskolaite or Cr oxide (Cr_2O_3). This indicated that at pre-oxidation temperatures $>1000\text{ }^\circ\text{C}$, e.g. $1400\text{ }^\circ\text{C}$ presented here, free Cr_2O_3 formed.

3.5 Theoretical thermochemical considerations

It is apparent, from the SEM and X-ray map results (Section 3.3), that higher pre-oxidation temperatures result in more Fe migration to the surface of the ore particles. The XRD analyses (Section 3.4) also indicate that pre-oxidising chromite ore at temperatures $>1000\text{ }^\circ\text{C}$ results in the formation of free Cr_2O_3 . In order to contextualise this information, these results are further explored with regard to their effect on the level of pre-reduction by means of relevant thermo-chemical calculations. An Ellingham diagram, constructed with the HSC thermo-chemical software package indicating the change in ΔG of the reduction of the relevant metal oxides with C and carbon monoxide (CO) is presented in Figure 3–4 (Kleynhans *et al.*, 2015). Although thermodynamic explanations of reactions ignore any kinetic effects, it is a useful tool. This Ellingham diagram is very similar to the diagram published by Niemelä *et al.* (2004).

Considering the thermo-chemical data presented in Figure 3–4, the following important deductions can be made:

- I. Fe oxide reduction takes place from the highest to the lowest oxidation state, i.e. hematite (Fe_2O_3) to magnetite (Fe_3O_4) to wüstite (FeO) to metallic Fe.
- II. CO (gas) can only serve as a reducing agent for FeO (the most reduced oxide state) to metallic Fe at temperatures $>710\text{ }^\circ\text{C}$. Although it is not shown in this figure, a high CO/ CO_2 ratio would also be required for such reduction to take place.
- III. Reduction of Cr-containing oxides is not possible with CO (gas).
- IV. Solid C can reduce FeO to metallic Fe at temperatures $>750\text{ }^\circ\text{C}$.
- V. Cr_2O_3 is reduced by solid C at temperatures $>1250\text{ }^\circ\text{C}$.
- VI. Synthetic Cr_2FeO_4 (which is similar to chromite (Niemelä *et al.*, 2004)) is reduced at lower temperatures than Cr_2O_3 , i.e. $1200\text{ }^\circ\text{C}$. In addition, eskolaite could form a sesquioxide solid solution with $\alpha\text{-Al}_2\text{O}_3$, which could significantly stabilise the Cr_2O_3 against reduction. Al_2O_3 and Cr_2O_3 are sesquioxides, having the same corundum crystal structure (approximately hexagonal close-packed oxide ions with the Al^{3+} and Cr^{3+} ions occupying two thirds of the available octahedral interstitial sites), which through

reaction at high temperatures ($T > 1000\text{ }^{\circ}\text{C}$) could form ranges of substitutional corundum-eskolaite, $\alpha\text{-(Al}^{3+}, \text{Cr}^{3+})_2\text{O}_3$ solid (Bondioli *et al.*, 2000).

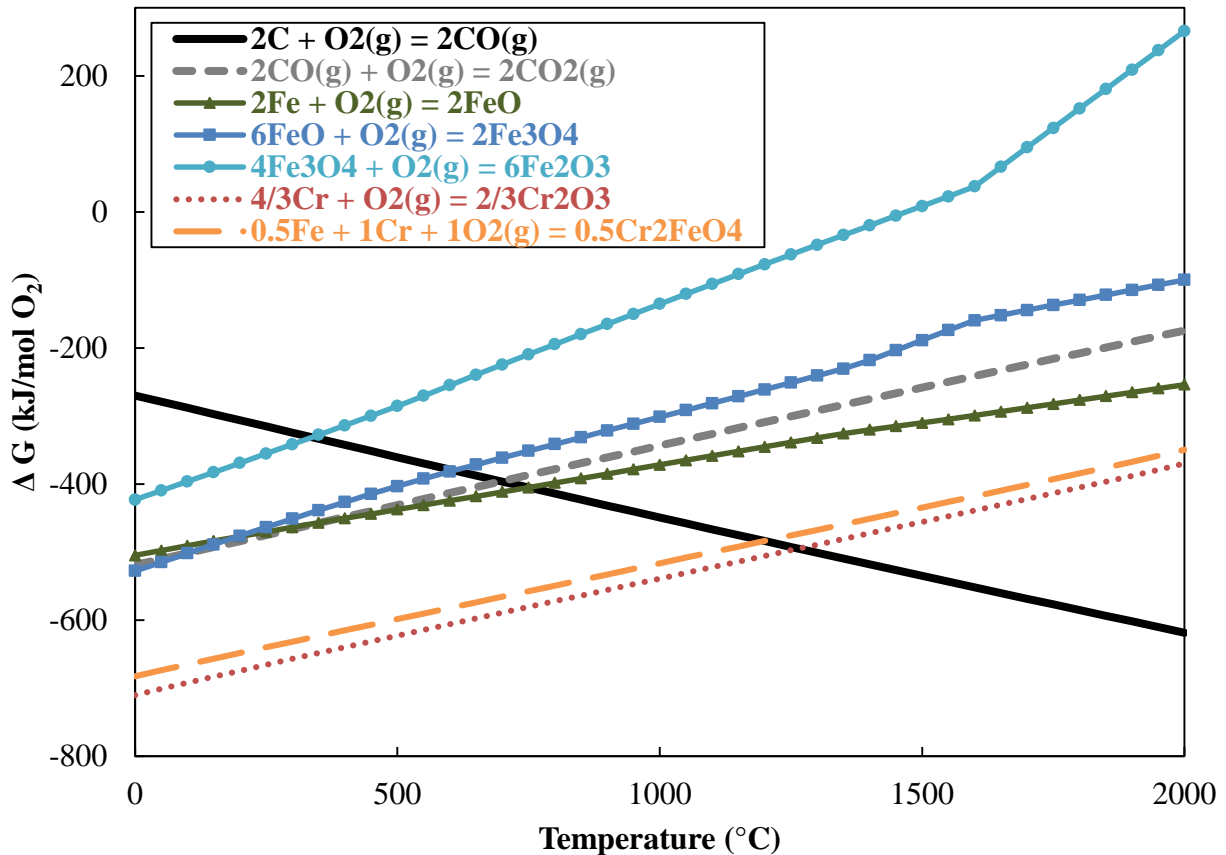


Figure 3–4: Ellingham diagram (ΔG as a function of temperature) indicating standard ΔG -free energies of reduction of metal oxides with solid C and CO, constructed with HSC thermo-chemical software (Kleynhans *et al.*, 2015).

The last three deductions, in particular, in conjunction with the SEM, X-ray map (Section 3.3) and XRD results (Section 3.4) can be used to explain the experimentally observed pre-reduction levels associated with increased pre-oxidation temperatures (Figure 3–1) (Kleynhans *et al.*, 2015). Since all Fe oxides can be reduced at temperatures $>750\text{ }^{\circ}\text{C}$, Fe migration to the surface of ore particles, as indicated by SEM and X-ray map data will enhance chromite pre-reduction levels. This provides a plausible explanation for the improved pre-reduction levels associated with increase in the pre-oxidation temperature of the ore up to $1000\text{ }^{\circ}\text{C}$. However, the XRD results indicated that free Cr_2O_3 is formed at pre-oxidation temperatures $>1000\text{ }^{\circ}\text{C}$, which counteracts the positive effect of Fe migration to the surface of the particle. This can be ascribed to Cr_2O_3 being more difficult to reduce than chromite. This explains the observed decrease in chromite pre-reduction levels at pre-oxidation temperatures $>1000\text{ }^{\circ}\text{C}$. The effect

of Cr_2O_3 formation at higher pre-oxidation temperatures was so significant, that pre-reduction levels were lower than that of un-oxidised ore (base case) at pre-oxidation temperatures ≥ 1200 °C (Kleynhans *et al.*, 2015).

Considering all that was presented thus far, it can be stated that chromite pre-reduction can be improved by means of utilising pre-oxidised chromite ore. The optimum pre-oxidation temperature would be the temperature at which a balance is obtained between maximising Fe migration to the surface of the ore particles and minimising the formation of free Cr_2O_3 . Kleynhans *et al.* (2015) documented the optimum pre-oxidation temperature to be 1000 °C for the specific fine metallurgical grade chromite ore utilised. Although the oxidation state of the Fe that migrated to the surface of the chromite ore particles was not determined by Kleynhans *et al.* (2015), Zhao and Hayes (2010) indicated that Fe_2O_3 enhanced reduction the most during the SAF smelting compared to the other oxides of Fe. Kapure *et al.* (2010) oxidised raw chromite ore in air for 2 hours at 900 °C using a chamber furnace. SEM micrographs and SEM-EDS analysis of raw (un-oxidised) chromite (A) and a pre-oxidised chromite particle (B) are shown in Figure 3–5.

During oxidation the Fe present in the form of FeO in the spinel is oxidised to Fe_2O_3 , forming an exsolved sesquioxide phase on the chromite mineral grain and generating additional cation vacancies. The sesquioxide phase precipitated onto the surface of chromite grain in a typical Widmanstätten pattern. Kapure *et al.* (2010) concluded that oxidation of chromite ore results in opening up of the spinel structure. Thus the newly formed Fe_2O_3 phase in conjunction with the additional vacancies generated during oxidation improves the reactivity of chromite ore and aids in slag formation at lower temperatures during reduction.

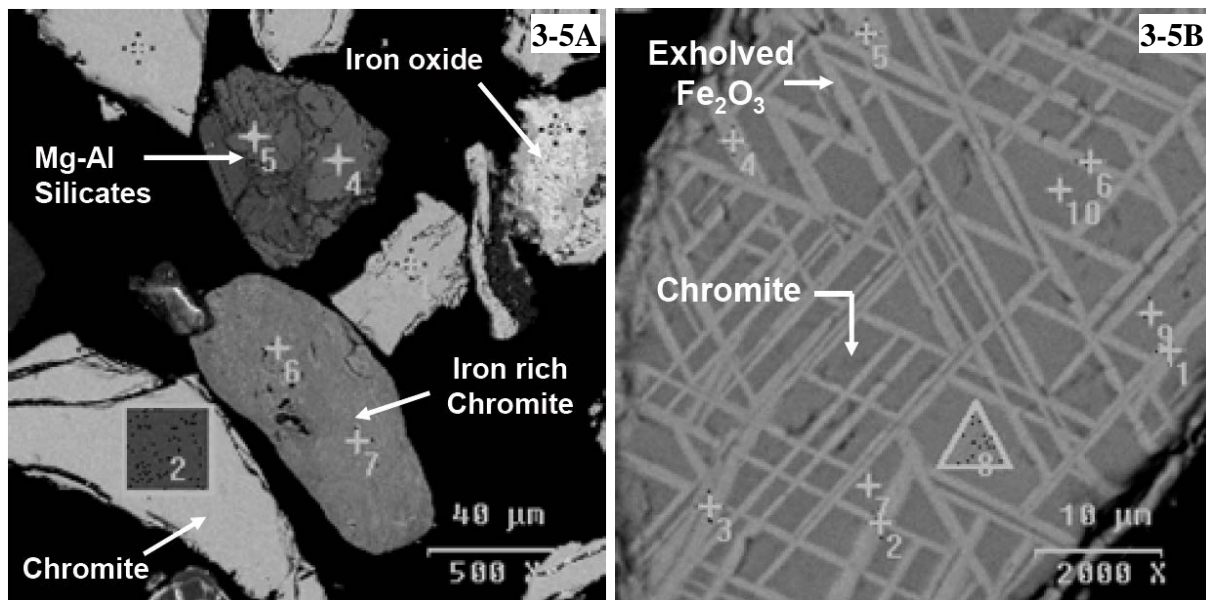


Figure 3-5A							Figure 3-5B			
Point	O	Mg	Al	Si	Cr	Fe	Point	Mg	Cr	Fe
1	22.7	11.7	8.4	0.5	46.9	7.7	1	7.3	45.9	15.5
2	23.3	10.3	7.9	0.6	46.4	10.9	2	4.2	47.1	28.8
3	21.2	0.0	1.7	2.7	2.4	71.3	3	3.3	47.2	20.2
4	31.9	10.6	3.5	32.0	0.3	11.3	4	2.0	47.8	22.5
5	32.2	11.1	1.7	34.1	0.4	12.1	5	0.0	46.6	26.1
6	26.4	0.5	7.3	3.1	30.9	30.0	8	12.5	46.8	9.3
7	24.5	0.0	7.7	2.9	37.2	25.8	9	12.6	46.7	8.8
8	22.7	10.2	7.0	0.7	47.8	10.2	10	13.3	47.4	8.6

Figure 3-5: SEM micrographs and SEM-EDS analysis of raw (un-oxidised) chromite (A) and a pre-oxidised chromite particle (B) (Kapure *et al.*, 2010)

3.6 Energy implications of pre-reduction alterations

Niayesh and Fletcher (1986) published data indicating the improvement in SEC, as a result of increasing chromite pre-reduction and feed material temperature. Similarly to (Neizel, 2013), reconstruction of this data and empirical fitting allowed evaluation of the effect of the level of pre-reduction achieved by using pre-oxidised ore on the SEC as presented in Figure 3-6. The effect of improved pre-reduction achieved by utilising pre-oxidised ore on the amount of FC (in the form of lumpy carbonaceous reductant) required to effect complete reduction of the pre-reduced pellets inside the SAF, is indicated in Figure 3-7.

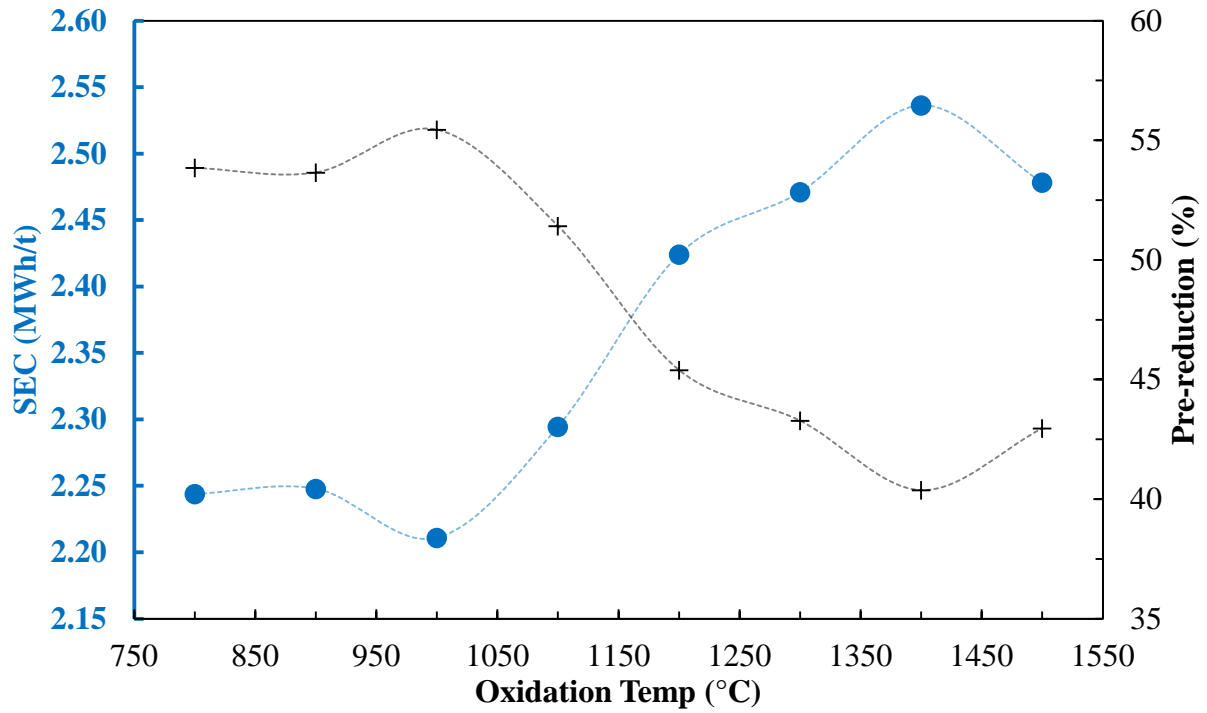


Figure 3–6: The effect of pre-oxidation temperature (x-axis) on the corresponding SEC (primary y-axis), as calculated from the reconstructed data by Niayesh and Fletcher (1986) at 27°C feed material

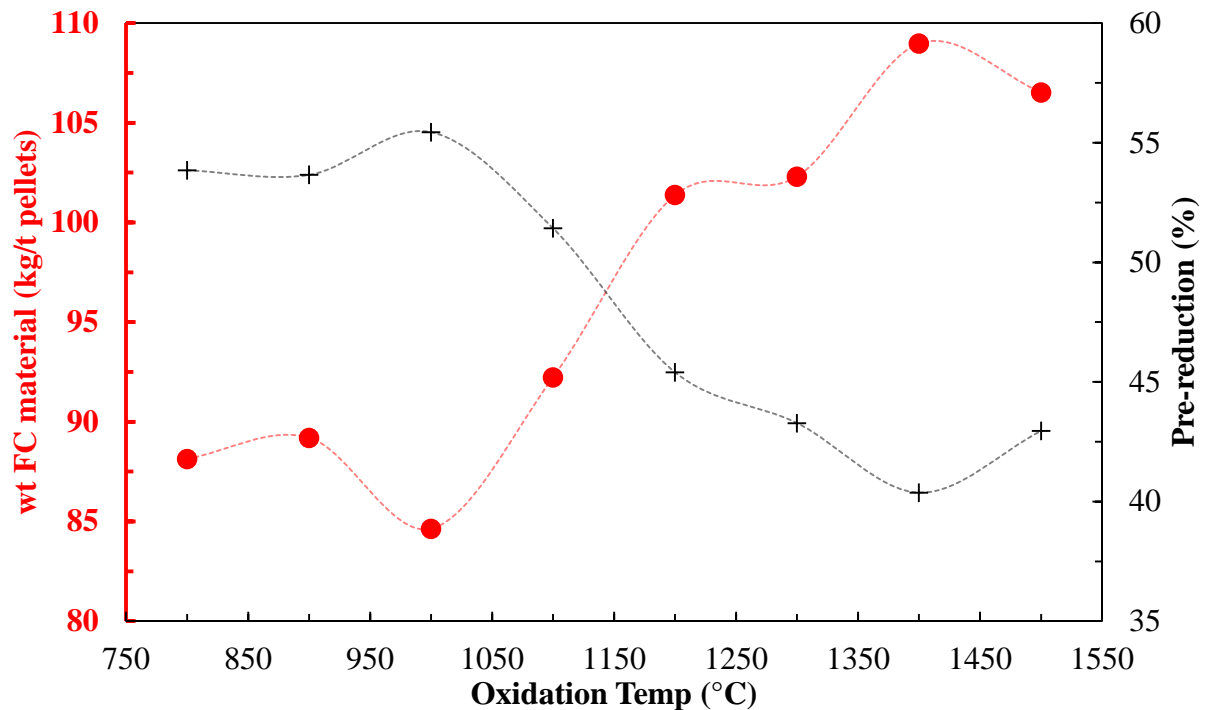


Figure 3–7: The effect of pre-oxidation temperature (x-axis) on the weight (wt) FC material required (kg) per ton pre-reduced pellets (primary y-axis)

The FC requirements were determined using the following equations:

$$wt\ FC\ for\ chromium\ oxide\ reduction = ((T.Cr\%) - (Sol.Cr\%)) \times 3.46 \quad 3-1$$

$$wt\ FC\ for\ iron\ oxide\ reduction = ((T.Fe\%) - (Sol.Fe\%)) \times 2.15 \quad 3-2$$

$$wt\ FC\ equivalent\ for\ Si\ and\ C\ in\ metal\ produced = (T.Cr\%) \times 1.684 \quad 3-3$$

$$wt\ FC\ required = (Total\ FC = (1) + (2) + (3)) - (Residual\ C = \frac{T.C\%}{100\%} \times 1000\ kg) \quad 3-4$$

In the above equation the Sol.Cr% and Sol.Fe% represent these metals in the metallised state in the pre-reduced pellets, while the T.Cr% and T.Fe% represent the totals of these metals in the pre-reduced pellets. Residual C is the C remaining in the pre-reduced pellets that were not consumed during the pre-reduction process and is calculated using T.C%, i.e. the percentage total C in the pre-reduced pellets. The constants used in the equations above were derived as follows:

From $Cr_2O_3 + 3C = 2Cr + 3CO$, the FC required for the metallisation of unreduced Cr is:

$$\frac{3\ mol \times 12.011\ g.mol^{-1}}{2\ mol \times 51.996\ g.mol^{-1}} \times \frac{1000\ kg}{100\%} = 3.46\ kg/\%$$

From $FeO + C = Fe + CO$, the FC necessary for the metallisation of unreduced Fe is:

$$\frac{1\ mol \times 12.011\ g/mol^{-1}}{1\ mol \times 55.845\ g/mol^{-1}} \times \frac{1000\ kg}{100\%} = 2.15\ kg/\%$$

The constant 1.684 is a typical value for South African FeCr alloys produced using the pre-reduction process and represents the C equivalent to the reduced Si and C contained in the metal produced.

From this data presented in Figure 3–6 and Figure 3–7, it is evident that an increase in the level of pre-reduction as a result of using pre-oxidised ore, could lead to significant improvements (decrease) in the SEC and lumpy carbonaceous material required in FeCr production, specifically at the pre-oxidation temperature of 1000 °C, where the SEC and FC required is at its lowest.

3.7 Effect of pre-oxidation on pre-reduction pellets mechanical strength

As previously stated, excessive fines present in SAF feed material could have disastrous consequences. It was therefore important to understand what effect pre-oxidation of chromite ore, prior to milling, agglomeration and pre-reduction, would have on cured pre-reduced pellet compressive and abrasion strengths. The compressive and abrasion strengths of the fired pellets are important in minimising degradation during handling, conveying, batching, and feeding the SAF furnace.

3.7.1 Compressive strength

Kleynhans *et al.* (2015) compared the compressive strengths of pre-reduced pellets produced from chromite ore that were pre-oxidised at different temperatures with the breaking strength of pre-reduced pellets made from un-oxidised chromite ore (base case, indicated with green dotted line). The pre-reduced pellets made from pre-oxidised ore were significantly weaker than pellets made from un-oxidised chromite ore (base case). As stated previously, pre-oxidation at 1000 °C resulted in the optimum pre-reduction level (Section 3.1). Compared with un-oxidised ore, pre-reduced pellets made from ore pre-oxidised at 1000 °C lost ~42% of their cured compressive strength (Figure 3–8A). It is difficult to contextualise these breaking strength results, since most of the previous studies focusing on improved chromite pre-reduction did not report pellet strength (Sundar Murti *et al.*, 1983; Van Deventer, 1988; Ding & Warner, 1997a; Ding & Warner, 1997b). Neizel *et al.* (2013), however, indicated that CaCO₃ addition, prior to milling, agglomeration and pre-reduction, lead to pre-reduced pellets losing more than 66% of their breaking strength. Therefore, pre-reduced pellets made from ore pre-oxidised at 1000 °C performed noticeably better.

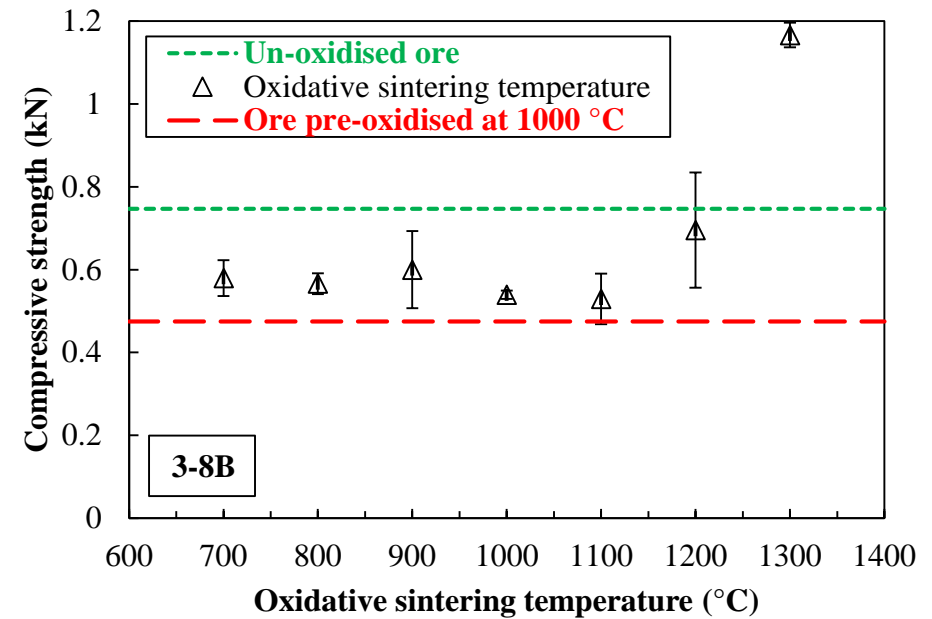
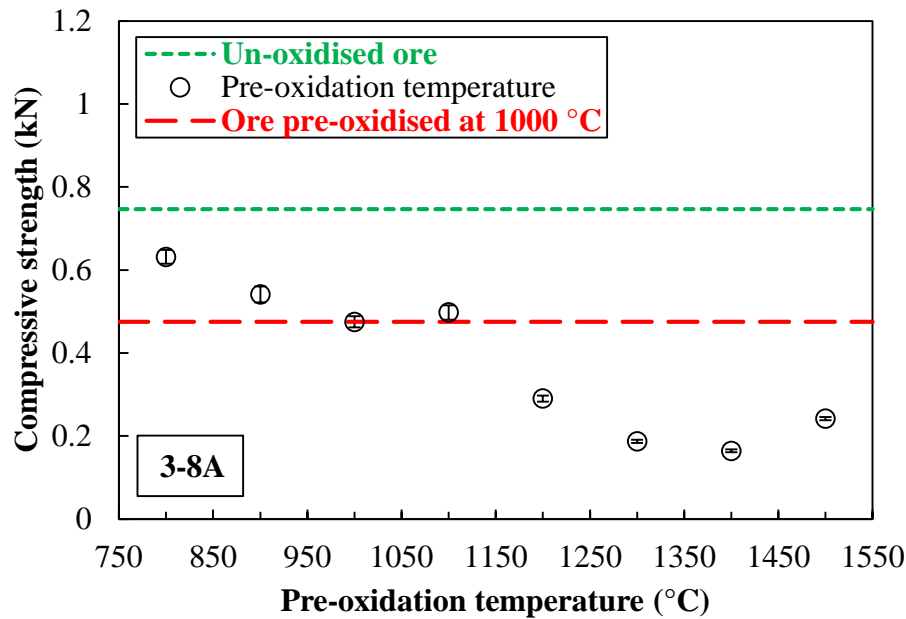


Figure 3–8: Graph A: The effect of pre-oxidation of metallurgical grade ore at different temperatures (x-axis) on the compressive strength of pre-reduced pellets (y-axis). Graph B: The compressive strength of pre-reduced pellets (y-axis), prepared from metallurgical grade chromite ore pre-oxidised at 1000 °C that were subsequently oxidatively sintered at different temperatures (x-axis) in a normal atmosphere. The bars indicate the standard deviations of results obtained for ten experimental repetitions (Kleynhans *et al.*, 2015).

It is important to note that all the afore-mentioned experiments were conducted in an inert (N₂ gas) atmosphere (Kleynhans *et al.*, 2015). However, Kleynhans *et al.* (2012) demonstrated that industrially produced pre-reduced pellets are not uniformly pre-reduced, since the atmosphere outside the pellet is usually partially oxidising. This leads to the formation of a thin oxidised outer layer, a transitional zone and a pre-reduced core. Kleynhans *et al.* (2012) also indicated that this thin outer oxidised layer contributed significantly to the strength of the pre-reduced pellets. Kleynhans *et al.* (2015) therefore investigated whether the presence of such a thin oxidised outer layer would significantly improve the pre-reduced pellet strength. Pre-reduced pellets, made from chromite ore that were pre-oxidised at 1000 °C, were subsequently exposed to oxidative conditions. These pre-reduced pellets, comprising of chromite ore pre-oxidised at 1000 °C, were placed in a laboratory tube furnace and the temperature ramped up from room temperature to the maximum desired temperature (700 to 1300 °C) under normal atmospheric gaseous conditions. When the desired maximum temperature was reached, N₂ gas was passed through the furnace to stop further oxidation. The pellets were then allowed to cool down within the furnace, where after compressive strength tests were conducted. These compressive strength test results are presented in Figure 3–8B. It is evident from these results that a considerable improvement in the pellet breaking strength was observed. This provided evidence that the presence of a thin oxidised outer layer will significantly increase the pellet strength, which will mitigate the decrease in compressive strength of pre-reduced pellets made from pre-oxidised ore (Figure 3–8A). Additionally, Kleynhans *et al.* (2015) also proved that pre-reduced pellet strength can be further significantly improved by selecting the optimum clay binder.

3.7.2 Abrasion resistance

In order to assess the effect of pre-oxidation of chromite ore on the abrasion strength of the pre-reduced pellet, Kleynhans *et al.* (2015) compared the abrasion strength of pellets prepared from pre-oxidised ore at 1000 °C with pellets made from un-oxidised ore. These results are presented in Figure 3–9.

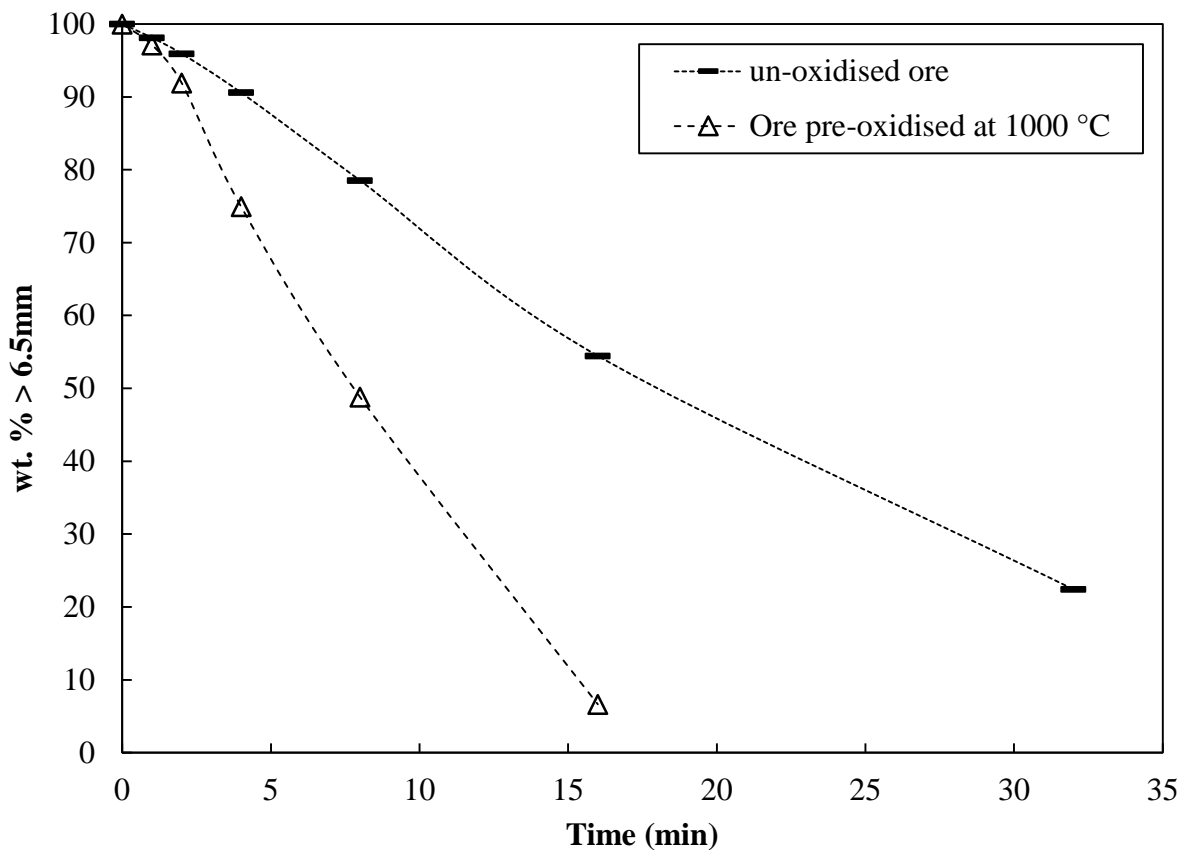


Figure 3–9: The effect of the pre-oxidation of metallurgical grade ore at 1000 °C on the abrasion strength of pre-reduced pellets indicated in weight percentage (wt. %) greater than 6.5 mm (y-axis) against abrasion time (x-axis) (Kleynhans *et al.*, 2015).

Similar to the above-mentioned compressive strength results, the abrasion strength of pre-reduced pellets made from chromite ore pre-oxidised at 1000 °C (the optimum temperature) lost some abrasion strength. However, this loss was lower than what was reported by Neizel *et al.* (2013) for CaCO₃ containing pre-reduced pellets. In addition, the abrasion strength of the industrially produced pre-reduced pellets will be enhanced by the presence of a thin oxidised layer, as indicated in the previous section (Section 3.7.1).

3.8 Thermomechanical analysis

Cold compressive and abrasion resistance strength tests give an indication of the cured strength of the pelletised materials after being treated in the different environments. However, the question could also be asked what the hot pellet strengths are, since that would influence pellet breakdown in the rotary kiln used in the industrial application. This has relevance to the formation or build-up of dam rings (material sticking to the inside of the rotary

kiln). A thermomechanical analysis (TMA) instrument measures the thermal expansion of material as a function of temperature. Although thermal expansion and shrinkage cannot be directly related to hot pellet strength, larger variation in thermal dimensional behaviour could possibly indicate weaker hot pellet strength (Kleynhans *et al.*, 2012).

In Figure 3–10, TMA analysis obtained from Kleynhans *et al.* (2015) of pellets prepared from un-oxidised chromite ore, and ore pre-oxidised at three different temperatures (800, 1000 and 1400 °C), which were pre-reduced in situ in the TMA, are presented. From these results it is evident that all the pellets had similar thermal dimensional change characteristics up to approximately 750 °C. However, at temperatures >750 °C, the pellets made from chromite ore that were pre-oxidised at 1400 °C indicated significant expansion, whereas the pellets made from ore pre-oxidised ≤1000 °C shrunk.

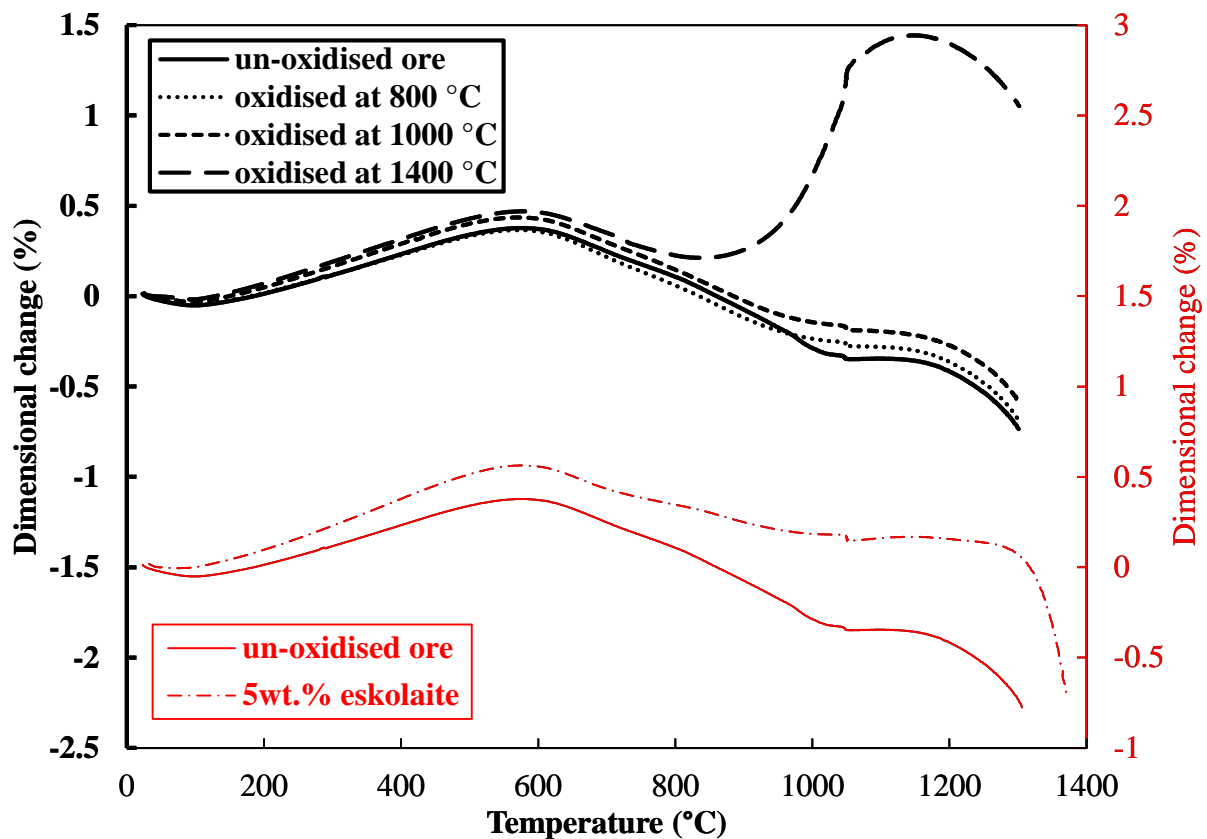


Figure 3–10: The average dimensional changes of pellets made from pre-oxidised ore (800 °C, 1000 °C and 1400 °C), that were pre-reduced in situ (primary y-axis), as well as the average dimensional change of pellets that contained 5 wt.% pure Cr₂O₃ (eskolaite), pre-reduced in situ (secondary y-axis) (Kleynhans *et al.*, 2015).

Kleynhans *et al.* (2015) speculated that the presence of Cr_2O_3 in the ore pre-oxidised at higher temperatures could be responsible for the above-mentioned different behaviours observed for these pellets due to the XRD analysis detecting the formation of free Cr_2O_3 in chromite ore pre-oxidised at 1400 °C (Section 3.4). In order to test this, Kleynhans *et al.* (2015) investigated the addition of pure Cr_2O_3 to un-oxidised ore prior to TMA, for which the result is shown in Figure 3–10 on the secondary y-axis. It is evident that the TMA curve of un-oxidised ore containing 5 wt% Cr_2O_3 exhibited similar characteristics to those obtained for the pellets made from pre-oxidised ore at 1400 °C, i.e. expanded at temperatures >750 °C. These curves are not a perfect match, since the matrixes differs somewhat, i.e. un-oxidised ore containing Cr_2O_3 and pre-oxidised ore. However, similar trend characteristics provided reasonable confirmation that the presence of Cr_2O_3 caused the pellets to expand at temperatures >750 °C. This also partially explains the decreased pellet strength associated with increased pre-oxidation temperatures (Figure 3–8).

3.9 Formation of Cr(VI) during chromite pre-oxidation

FeCr production from chromite ores occur at high temperatures under a reducing environment. However, it is impossible to completely exclude oxygen from all high temperature process steps and, although unintended, the possibility arises for the formation of small amounts of Cr(VI) species (Beukes *et al.*, 2010). Certain Cr(VI) species are regarded as carcinogenic, with specifically airborne exposure to these Cr(VI) species being associated with cancer of the respiratory system (Thomas *et al.*, 2002; Beaver *et al.*, 2009). Kleynhans *et al.* (2015) quantified the amount of Cr(VI) that could be formed if chromite ore is pre-oxidised, prior to pre-reduction. The report indicated that 0.4 to 1 µg Cr(VI) per gram pre-oxidised ore (µg/g or g/metric ton) is formed during pre-oxidation. These Cr(VI) levels are substantially lower than the Cr(VI) content reported for typical semi-closed SAF FeCr furnace off-gas, which varies between 5 and 7000 µg/g (g/metric ton) (Gericke, 1995). The substantial lower Cr(VI) levels in pre-oxidised ore compared to levels reported in furnace off-gas can most likely be attributed to the metallurgical grade chromite ore not being milled prior to pre-oxidation, which limited the surface area exposed to oxidation. Milling prior to pre-oxidation would increase the risk of the Cr(VI) becoming airborne, which increases the risk of inhalation and should be taken into consideration during process development.

3.10 Conclusions

Fundamentally, pre-oxidation of chromite ore prior to milling, agglomeration and pre-reduction significantly enhance the level of chromite pre-reduction achieved in the pelletised chromite pre-reduction process. This has a corresponding positive effect on the SEC and lumpy carbonaceous material required for smelting in the SAF during FeCr production. By pre-oxidising chromite ore in the temperature range of 800 to 1100 °C, the level of achievable chromite pre-reduction improved, with pre-oxidation at 1000 °C established as being the optimum temperature. Theoretically this correlates with an 8.5% improvement in the SEC (from ~2.4 to ~2.2 MWh/t) and a 14% decrease (from ~99.5 to ~85.5 kg/t pellets) in the amount of lumpy carbonaceous material required during SAF smelting. However, pre-oxidation temperatures above 1100 °C result in decreased levels of pre-reduction with pre-oxidation temperatures higher than 1200 °C resulting in pre-reduction levels even lower than the pre-reduction level obtain by utilising un-oxidised ore. SEM and X-ray map images indicated that by pre-oxidising the chromite ore, Fe from the spinel migrated to the surfaces of the ore particles, which will enhance pre-reduction of chromite, since Fe oxides reduce at relatively low temperatures. XRD provided evidence of the formation of free Cr₂O₃ (eskolaite) at pre-oxidation temperatures exceeding 1100 °C. According to thermo-chemical calculations reduction of Cr₂O₃ by solid C requires a higher temperature compared to chromite, hence the decreased pre-reduction if the ore is pre-oxidised >1100 °C.

Pre-oxidation of the chromite ore noticeably decrease pellet compressive and abrasion strengths. This increases the risk of pre-reduction pellet degradation, which is negative for SAF FeCr production. However, the decreased pellet strength will be significantly mitigated by the presence of a thin oxidative outer layer on the industrially produced pre-reduced pellets, which can further be mitigated if an optimum clay binder is selected. TMA results indicated that Cr₂O₃ formation during the pre-oxidation of the chromite at >1100 °C ore was responsible for additional thermo-dimensional change and possibly the afore-mentioned weaker pellet strengths.

Small amounts of Cr(VI) can form during the pre-oxidation of the chromite ore, however, these levels were well below that of current fine FeCr waste materials. If this process is implemented on an industrial scale, the appropriate preventative measures need to be taken to prevent negative health effects of Cr(VI).

Techno-economic feasibility of a pre-oxidation process to enhance pre-reduction of chromite

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Techno-economic feasibility of a pre-oxidation process to enhance pre-reduction of chromite

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Synopsis

Ferrochrome (FeCr) is vital to the production of stainless and high-alloy ferritic steels, since it is the only source of new Cr units. FeCr production is an energy intensive process. The pelletised chromite pre-reduction process is most likely the FeCr production process with the lowest specific electricity consumption (SEC), i.e. MWh/ton, currently in operation. However, due to increases in costs, efficiency and environmental pressures, FeCr producers applying the afore-mentioned process are still attempting to achieve even lower overall energy consumption. Recently it was proven that pre-oxidation of chromite ore, prior to pelletised pre-reduction, significantly decrease both the SEC and lumpy carbonaceous reductants required for furnace smelting. This paper presents the first attempt at conceptualising the techno-economic feasibility of integrating chromite pre-oxidation into the pre-reduction process. Financial modeling yielded a net present value (NPV) at an 10% discount rate of

~ZAR 900 million and an internal rate of return (IRR) of ~30.5% after tax, suggesting that implementation of pre-oxidation prior to pelletised pre-reduction may be viable from a financial standpoint. Sensitivity analysis indicated that the parameter with the greatest influence on project NPV and IRR is the level of pre-reduction achieved. This indicated that the relationship between maintaining the optimum pre-oxidation temperature and the degree of pre-reduction achieved is critical to maximise process efficiency.

Keywords: Chromite pre-reduction, Solid state reduction of chromite (SRC), Pre-oxidation of chromite, Discounted cash flow (DCF) model, Techno-economic feasibility

Introduction

Stainless steel is a crucial alloy in modern society. Virgin chromium (Cr) units used in the manufacturing of stainless steel are obtained from ferrochrome (FeCr) – a relatively crude alloy consisting predominantly of Cr and iron (Fe) (Murthy et al., 2011, Beukes et al., 2012). FeCr is mainly produced during the pyrometallurgical carbo-thermic reduction of chromite ore, mainly in submerged arc furnaces (SAFs) and direct current arc furnaces (DCFs) (Neizel et al., 2013, Beukes et al., 2010, Dwarapudi et al., 2013). In the afore-mentioned processes, electricity supplies the energy required to heat, smelt and reduce the chromite ore to the metallised state (Pan, 2013). FeCr production is an energy intensive process, with specific electricity consumption (SEC) i.e. MWh/ton FeCr produced, varying from 2.4 to more than 4.0 MWh/ton FeCr produced, depending on the process applied (Pan, 2013, Neizel et al., 2013). Daavittila et al. (2004) stated that the typical operational costs of FeCr smelters can be divided into four cost categories, i.e. chromite ore (30%), carbonaceous reductant (20%), electricity (30%) and other production costs (20%). This makes electricity consumption the joint largest factor that influences operational costs in FeCr production. Beukes et al. (2010) presented an overview of processes utilised for FeCr production, referring specifically to the South African FeCr industry. However, similar processes are also applied internationally. According to this review (Beukes et al., 2010), FeCr is produced via (i) conventional semi-closed/open submerged arc furnace (SAF) operation, with bag filter off-gas treatment; (ii) closed SAF operation that usually utilises oxidised sintered pelletised feed, with venturi scrubbing of off-gas; (iii) closed SAF operation consuming pre-reduced pelletised feed, with venturi scrubbing of off-gas; and (iv) closed direct current (DC) arc furnace operation, with venturi scrubbing of off-gas. Until now these processing options have allowed for economical FeCr production,

particularly in countries with local chromite resources (Daavittila et al., 2004).

Although equipment has been technologically advanced and modern automation systems implemented, there still exist some significant technological limitations in the smelting of chromite, i.e. (i) the efficient use of energy (i.e. electricity and chemical energy in the form of reductants) and the utilisation of secondary energy produced (e.g. CO-rich off-gas, radiation heat), (ii) increased use of lower cost raw materials through advanced beneficiation and agglomeration, or corresponding technologies, (iii) enlarged production units in order to benefit from the large scale economies and (iv) higher degrees of automation to improve operation (Daavittila et al., 2004). These limitations, coupled with the fact that SAF and DC smelting operations can be regarded as having reached the 'mature' phase of its evolutionary development, indicate that FeCr producers and their main customers, the stainless steel producers, should consider more cost and quality effective production of Cr units (Slatter, 1995, Holappa, 2010). FeCr producers face significant challenges that will require innovative advances in FeCr production process technologies (Ugwuegbu, 2012), e.g. downward trend in FeCr prices, increasing awareness of environmental impacts and working conditions, increasing electricity costs (and availability thereof in some countries) and carbon footprint reduction requirements (Daavittila et al., 2004).

In the past various measures to improve FeCr production with the SAF process have been investigated (Kapure et al., 2010, Daavittila et al., 2004, Slatter, 1995, Goel, 1997, Ugwuegbu, 2012). These developments mainly included pre-reduction and preheating methods in order to improve Cr recoveries and minimise smelting costs. The pelletised chromite pre-reduction process (commercially known as the Premus process), applied by two Glencore Alloys FeCr smelters in South Africa (RSA) (with six large smelting SAFs), is considered to be the FeCr production process option with the lowest

SEC currently in operation (Kleynhans et al., 2012). Similar smelters are being commissioned in China, but no information regarding these operations is currently available in the peer reviewed public domain. The SEC of the pelletised chromite pre-reduction process is approximately 20% lower than that of its nearest rival, the SAF smelting process with oxidised sintered pellets as furnace feed (commercially referred to as the Outotec technology) (Neizel et al., 2013). The pelletised chromite pre-reduction process also has some disadvantages as indicated by Mohale (2014), i.e. the higher capital cost and the extensive operational control that is required due to the variation in pre-reduction levels and carbon contents of the pre-reduced pelletised furnace feed material.

In view of the previously mentioned challenges faced by FeCr producers and regardless of the lower SEC of the pelletised chromite pre-reduction process, it is apparent that smelters applying the afore-mentioned process would benefit from a process improvement capable of achieving even lower SEC. Beukes et al. (2015) developed a new process during which chromite ore is subjected to oxidation before it is used as feed material for pre-reduction that was patented, while Kleynhans et al. (2015) reported on this patent in the public peer reviewed domain. In principal the afore-mentioned authors found that pre-oxidation enhanced the susceptibility of the chromite spinel to be pre-reduced, mainly by Fe liberation and preventing the release of chromium(III)oxide (Cr_2O_3) from the spinel (Beukes et al., 2015, Kleynhans et al., 2015). As indicated by Niayesh and Fletcher (1986) an increase in the level of pre-reduction will result in a decrease in SEC. It is claimed by Beukes et al. (2015) and Kleynhans et al. (2015) that a reduction in SEC of ~8.5% can be achieved by the afore-mentioned patented process. Therefore, the aim of this paper was to investigate the economic feasibility of the patented pre-oxidation process applied as a pre-treatment to

the pelletised chromite pre-reduction process and to evaluate the extent of the impact of integration of this process on the economics of a typical FeCr smelter applying pelletised chromite pre-reduction. Through an analysis of cost efficiency for various cost model parameter options, as well as their subsequent development within a comprehensive cost model and discounted cash flow (DCF) model, the long-term feasibility of integrating such a pre-oxidation process with an existing smelter applying the pelletised chromite pre-reduction is evaluated.

Feasibility study backdrop

RSA holds the majority of global chromite reserves (Beukes et al., 2012, Merafe-Resources, 2012, Creamer, 2013). The majority of RSA's chromite ore is relatively friable. It is thus common to only recover 10 to 15% lumpy ore (15 mm < typical size range < 150 mm) and 8 to 12% chip/pebble ores (6 mm < typical size range < 15 mm) during the beneficiation process employed after chromite mining. The remaining ore would typically be in the < 6 mm fraction, which would usually be crushed and/or milled to < 1 mm and then upgraded utilising gravity separation techniques (e.g. spiral concentrators) to ~45% Cr₂O₃ content. This upgraded < 1 mm ore is commonly known as metallurgical grade chromite ore (Glastonbury et al., 2010). Additionally, upgraded fine (< 1mm) UG2 process residue from the platinum group metals (PGMs) industry is also available as chromite feed material to the South African FeCr industry (Cramer et al., 2004).

Effective SAF smelting operation desires a permeable burden to ensure uniform flow of reduction gases and smooth furnace operation (Dwarapudi et al., 2013). The use of fine chromite ore in SAFs is limited, since fine materials increase the tendency of the surface layer of the SAF burden to sinter. This traps evolving process gas, which

can result in so-called bed turnovers or blowing of the furnace that could result in damage to equipment or injury to personnel. A process that can accommodate fine ore is thus required, typically one where an agglomeration step (e.g. pelletisation) prior to feeding into the SAF is employed (Kleynhans et al., 2012, Beukes et al., 2010).

RSA, at present, has fourteen separate FeCr production facilities with a combined production capacity in the region of ~5.2 million t/a (Beukes et al., 2012, Jones, 2015). The abundant chromite resources and comparatively low historic cost of electricity have contributed to RSA maintaining the dominant position in the international FeCr industry, contributing on average 44.5% to the global FeCr production in the period 2000-2011. However, in 2012 it produced only 32% of the world's output as production decreased by 30% from 2007, with China becoming the largest FeCr producer (ICDA, 2013b). A number of factors led to this major downturn in the RSA FeCr industry. Firstly, RSA is facing several internal challenges that have negatively impacted the manufacturing ability and production cost of FeCr producers. Historically, the country benefited from favourable, inexpensive logistics and relatively cheap labour. In the present day this is no longer the case, since RSA is experiencing energy and labour problems. By the end of 2007 electricity demand of RSA caught up with its electricity generating capacity. In order to avoid destabilisation of the national electricity grid, rolling blackouts was implemented. Erosion of surplus generation capacity led to a dramatic increase in the nominal price of electricity, increasing by ~245% from 2007 to 2013 (Eskom, 2012). In 2012, Eskom, the country's state-controlled, energy supplier, realised that it would not be able to support total electricity demand and agreed to reimburse FeCr smelters to not use already contracted electricity supply and to temporarily shut down their furnaces. This lack of energy-generation capacity is the result of years of underinvestment in the electricity sector. FeCr

smelters, facing low prices for the alloy, welcomed the proposition and started to shut down their furnaces. Anecdotal evidence indicated that it was more profitable for them to sell energy back to Eskom than to produce FeCr. In addition, in order to deal with this major energy crisis, Eskom announced in early 2013 that it needed ZAR50 billion (approximately US\$5 billion) more than planned to meet funding needs in the next five years until 2018. This was in addition to the ZAR225 billion shortfall in revenue due to higher coal prices and increased capex expenses. Eskom needed to invest immensely in new capacity, but the National Electricity Regulator of RSA (NERSA) refused the price increase of 16% per year requested by Eskom for the multiyear price determination period of 2013-2018. Instead, NERSA granted Eskom permission to raise the energy tariff by 8% per annum for the next 5 years, to finance investments in new electricity capacity. Furthermore, Eskom struggles to find the coal it requires. Coal production has to rise from the current 254 million t/a to more than 320 million t/a by 2020 to satisfy the state-owned power utility's demand. Finally, as a result of the first factor, RSA's main FeCr buyer, i.e. China, had increased domestic FeCr production and reduced imports thereof, taking advantage of the increasing demand for FeCr and filling the gap in the market. Lower shipping costs, brought about by the slowdown in the world economy, made geographical positioning of smelters less relevant. Therefore, at present RSA ships less FeCr to China, which now imports more chromite ore from RSA, with China smelting it locally and supplying most of its own FeCr to its own stainless steel industries (ICDA, 2013a, ICDA, 2013b).

Considering the above-mentioned background, the South African FeCr industry is an ideal economic environment to serve as the backdrop for this feasibility study. RSA holds the majority of the world's chromite resources, the ore is friable that

necessitates an agglomeration process step and the energy situation also justifies exploring new FeCr production technologies to reduce SEC.

Process options

Although the pre-oxidation process prior to pre-reduction has been patented (Beukes et al., 2015), the pre-oxidation process prior to pre-reduction has not yet been applied on an industrial scale. The process therefore needs to be matched with appropriate equipment. Equipment used in currently applied and previously attempted pre-treatment options could be considered to serve for this purpose, i.e.:

I) Outotec's Steel Belt Sintering process is the only commercially applied FeCr process where oxidation as a pre-treatment method prior to smelting in the SAF is utilised. Pre-oxidation of unagglomerated chromite ore prior to pre-reduction (solid state reduction of chromite) must not be confused with oxidation prior to smelting. Also, reduction, as taking place during smelting in a SAF when the ore is completely reduced to the zero oxidation or metal state, must not be confused with pre-reduction where the ore is only partially reduced. Molten or liquid materials are formed during the smelting reduction process in contrast to the absence of molten or liquid phases being formed during the pre-reduction process, hence the alternative name "solid state reduction of chromite". The primary raw materials in the Outotec steel belt sintering process, which has been the most commonly applied process over the last decade in the South African FeCr industry, are ore fines, a refined clay binder, and fine coke. The ore and coke are wet-milled in a ball mill up to ~90% of the particles smaller (d_{90}) than 108 μm (Glastonbury et al., 2015) and de-watered in capillary-type ceramic filters. The de-watered material is mixed with a clay binder and pelletised in a drum pelletiser before finally being sintered in the steel belt sintering furnace. The fixed carbon (FC)

content (from coke fines) added in the steel belt sintering feed mixture is low (~1-2%) compared to the FC content of the feed mixture for pre-reduction (~12.5-15%). The sintering process is basically an oxidative process, during which the carbon present in the pellets is oxidised to sinter the pellets (Beukes et al., 2010, Glastonbury et al., 2015).

II) In rotary hearth furnace technology, normally applied as a preliminary heating or reduction step prior to smelting, ore, reductants, and fluxes are milled to less than typically 100 μm before being blended, mixed, and fed into a pelletising plant. The green pellets are dried using exhaust gas from the rotary hearth furnace. The furnace operates continuously and the pellets are sintered, reduced, and cooled in controlled zones with a maximum zone temperature of 1450 $^{\circ}\text{C}$ (Slatter, 1995). The reduction occurs in stages in different zones of the furnace. Additional hot air is introduced into the rotary hearth furnace to control the temperature and the composition of the atmosphere in order to provide conditions conducive to the optimal reduction of chromite and minimisation of re-oxidation. Once the material has passed through the rotary hearth furnace, it is discharged and can be cooled using various methods. Energy for the sintering and pre-reduction zones can be provided by the oxidation of the CO gas obtained from the exhaust gas of SAFs (Slatter, 1995). By operating this furnace with an oxidising atmosphere, it could be applied as a pre-oxidation process.

III) Fluidised-beds are ideally suited for processing of finely sized raw materials (Luckos et al., 2007). Since the fluidised-bed can be used as a pre-heater for chromite, it can also be considered as a means to pre-oxidise ore prior to pre-reduction. Laboratory-scale pre-heating tests with chromite ores and coals were carried out in a fluidised-bed facility at Lurgi Metallurgie, which was followed by a pilot-scale test in a four-stage flash preheater at Polysius AG. These tests confirmed that chromite ores and fluxes can be thermally treated up to a gas temperature of 1150 $^{\circ}\text{C}$ without succumbing

to the forces of attrition and producing fines, or forming low-melting point phases and agglomerating. Denton et al. (2004) stated that the best option from an economic point of view is to use CO-rich furnace off-gas to pre-heat the chromite and fluxes to 1200°C.

IV) The rotary kiln serves as the process unit for a number of pre-heating and pre-reduction process technologies. In principle, rotary kilns can be effectively used for preheating charge by making use of CO-rich furnace off-gas. The use of a rotary kiln for pre-reduction of chromite ore was developed and applied on an industrial scale by three companies, i.e. Outokumpu, Showa Denko and Krupp/MS&A (McCullough et al., 2010, Ugwuegbu, 2012). Outokumpu used a rotary kiln for preheating pellets up to 1000 °C before continuously feeding the pre-heated pellets to a closed SAF.

Outokumpu studied its process for approximately ten years on laboratory and pilot scale, as well as for two years in a commercial scale operation. The process consisted of a rotary kiln with a length of 55 m and an inner diameter of 2.3 m (Daavittila et al., 2004). The process involved grinding and pelletising of ore fines, followed by sintering of green pellets that were pre-reduced before smelting. The ore and coke fines used by Outokumpu were wet-ground to approximately d₃₅ of 37 µm and then pelletised up to approximately 15 mm diameter. The bulk of the fuel for sintering and pre-reduction of the pellets was provided by CO off-gas from closed SAFs (Goel, 1997). Showa Denko's process that pre-reduces pellets is currently still in use. It was installed by Consolidated Metallurgical Industries in RSA in the mid-1970s. This was the first commercial pre-reduction process for chromite. In this process, chromite ore fines are milled to d₉₀ <75µm, pelletised with coke as reductant, and fired in a rotary kiln to approximately 1400 °C. The kiln is heated by a pulverised coal burner. The pellets with approximately 40 to 60% metallisation of Cr and Fe are discharged into a SAF for final smelting (Naiker, 2007, Naiker and Riley, 2006). To address some of the apparent

weaknesses of the Showa Denko K.K. (SDK) Process, Krupp commenced development of a rotary kiln pre-reduction process in 1984, based upon their CODIR Process. In this process chromite ore and coal fines react in a rotary kiln at temperatures approaching 1450°C to produce a semi-solid product consisting of highly metallised FeCr, slag, gangue and char. High temperature and intimate contact between the chromite grains and carbon are necessary over the entire residence time in the kiln in order to achieve a high degree of metallization (>90%). For this purpose, the burden is transformed into a semi-solid state with a combination of molten and solid phases, to allow for only a small portion of the surface of the metallised phase to be exposed to air without macroscopic phase separation occurring (McCullough et al., 2010). The Premus process, currently applied by Glencore Alloys, was developed from the SDK/CMI process. In this process anthracite or char is used as a reductant instead of coke. Similarly to the SDK/CMI process, the raw materials are dry milled, pelletised, pre-heated and fed into a rotary kiln. Pure oxygen and a pulverised carbon fuel (PF) are used to fire the kiln (Basson et al., 2007, Naiker, 2007, Naiker and Riley, 2006, Ugwuegbu, 2012). Kleynhans et al. (2012) indicated that while the pellets are exposed to the high temperatures inside the rotary kiln, the carbon in the outer layer of the pellets is mostly burned off and a partially oxidised outer layer is formed. A small amount of Fe reduction can occur before all the carbon is consumed in this outer layer, which can be re-oxidised again. Oxygen ingress to the core does not take place, since CO gas formed from the carbon inside the pellets produces a positive partial pressure. This positive CO pressure is therefore necessary to prevent re-oxidation of the pellets. If chromite ore is fed into the kiln without a carbon reductant to generate CO, natural oxidation would thus occur as required for the pre-oxidation process.

The disadvantage of Option I, the Outotec steel belt sintering process, is that the raw materials used, including the ore, are milled and pelletised before being sintered in an oxidising environment. In order to use the oxidised pellets in the pre-reduction process, these pellets would have to be pulverised. The energy and raw materials used to initially pelletise the ore for pre-oxidation would therefore be wasted. The rotary hearth furnace and fluidised-bed processes, Option II and III, offer an interesting alternative; however, although tested on pilot scale, these processes have not yet progressed to successful large-scale operation within the FeCr industry and further development is required. Considering the above-mentioned four options the one most likely to be implemented by FeCr producers already utilising the pre-reduction process is the option employing a rotary kiln. FeCr producers using chromite pre-reduction are accustomed to kiln operation and would prefer this route as it fits within their current pre-reduction operations culture. It also has an advantage from a maintenance perspective, i.e. employing a kiln with the same diameter for pre-oxidation as the kiln used for pre-reduction. This standardisation of equipment components would reduce spare parts required, thus lowering capital that is tied up.

Process descriptions

Since it is expected that a counter current rotary kiln will be used if the pre-oxidation process is implemented at a smelter already applying the pelletised chromite pre-reduction process (see discussion in preceding section), a hypothetical process flow diagram was developed consisting of a rotary kiln and auxiliary equipment. This flow diagram, together with the flow diagram of the current industrially applied pre-reduction process is presented in Figure 1A and B, respectively. In the chromite pre-oxidation process (Figure 1A) fine chromite ore is fed into holding silos. The ore is then fed with weight feeders onto a conveyor and that enters the kiln. The oxidation of the ore in the

rotary kiln is achieved with thermal energy supplied by pulverised coal and/or furnace off-gas at the discharge end of the kilns. A gas fan at the feed end pulls air through the kiln that is sent to a cyclone to remove coarse particles (<1 mm) where after it passes through a bag house to remove finer particles (<30 µm) before being released into the atmosphere (Pšunder, 2012). The pre-oxidised fine chromite ore (OC) is then discharged into a bunker and transported to the pre-reduction raw material storage heaps. The oxidising temperature inside the kiln is controlled by measuring the ore discharge temperature with an optical sensor. The pre-oxidised fine chromite ore is then fed as raw material into the pre-reduction process (Figure 1B), instead of normal chromite ore. The pre-reduction and smelting process flow (Figure 1B) is not discussed here, since various publications presented detailed discussions (Ugwuegbu, 2012, Naiker, 2007, Naiker and Riley, 2006, Botha, 2003). The off-gas produced during SAF smelting are cleaned through a venturi water scrubbing system and recycled, specifically to the chromite pre-oxidation process, to serve as an energy fuel source.

Insert Figure 1

Methodology

Quantification of process benefits associated with chromite pre-oxidation

From experimental results presented by Kleynhans et al. (2015) it is evident that the level of pre-reduction could be considerably enhanced through the pre-oxidation of chromite ore prior to pre-reduction. The advantages of improved pre-reduction can be observed in several aspects of operation. However, the two main advantages include the decrease in SEC and lumpy carbonaceous reductants required for SAF operation.

Niayesh and Fletcher (1986) published a graph of chromite pre-reduction as a function of SEC, for different temperatures of pre-reduced feed material. Kleynhans et al. (2015) reconstructed and empirically fitted the data published by Niayesh and Fletcher (1986) to estimate the improvement in SEC. Furthermore, Kleynhans et al. (2015) also used the fundamental carbon based metallisation and reduction reactions for chromite presented by Barnes et al. (1983) to calculate the decrease in FC content associated with the lumpy reductants fed into the SAF. If it is assumed that pre-oxidation of the chromite takes place at 1000°C the improvements in both the afore-mentioned parameters, i.e. SEC and FC requirement, due to pre-oxidation are presented in Figure 2.

Insert Figure 2

From Figure 2 it is evident that less FC is required for smelting in the furnaces with an increase in pre-reduction. Although one could directly calculate the electric energy financial gain from the improved SEC, annual FeCr production capacity and current price of electricity, this is not a true reflection of the financial advantage that can be achieved. An electric arc furnace is designed according to a specific apparent power (S). However, only a fraction of this power, called the power factor (K_p), is available as electrical energy for smelting. This total available electrical energy, called the active power (P), is a constant and cannot be changed. The production capacity of an operation is determined by dividing the active power by the SEC. Thus, since the total energy available cannot be changed, the benefit of improved or lower SEC is observed as an increase in the operations production capacity. This implies that as a result of an

increase in pre-reduction levels, for the same total available electrical energy, FeCr production is increased.

Cost distribution

The typical cost factors for the FeCr industry in European conditions was presented by Daavittila et al. (2004). According to Biermann et al. (2012) the cost factors for South African FeCr smelters varies to some extent; with chromite ore, reductants, and electricity each accounting for 30% of the production costs, while factors such as maintenance, labour and waste disposal account for the remaining 10%. An analysis of South African FeCr input costs conducted by Cartman (2008) differed from Biermann et al. (2012), with chromite ore accounting for 38%, electricity for 18%, reductants and other raw materials for 24% and maintenance, overheads and labour for 20%. The difficulty in interpreting these cost distributions is that in none of these references were the process(es) to which the cost distribution was linked, mentioned. Therefore it can be any of the process combinations mentioned in the 'Introduction' section (Beukes et al., 2010) and cost distribution for different process combinations will certainly vary. In order to conduct the financial modeling, it was important to consider life cycle costs associated with the implementation of the chromite pre-oxidation process and the cost distribution of the chromite pre-reduction smelting operation. Since previously cited FeCr costs estimates (Daavittila et al., 2004, Biermann et al., 2012, Cartman, 2008) did not focus specifically on the pre-reduction process, a life cycle cost factor breakdown of the chromite pre-oxidation process in combination with the pre-reduction process was developed, as illustrated in Figure 3.

Insert Figure 3

The life cycle costs for both the chromite pre-oxidation process and pre-reduction process was divided into initial development costs (e.g. environmental impact assessment, design), capital costs, operating costs and decommissioning costs, with the operating costs for both processes being sub-divided into fixed and variable costs. As mentioned in the previous section the effect of increasing the pre-reduction level, results in a decrease in the reductant content required for smelting in the furnace, as well as an increase in production capacity with the same total active power. Therefore, from a cost distribution perspective, both the electricity and reductant cost factors ($R/t \text{ FeCr}$) is lowered for the pre-reduction process, while production capacity is increased (refer to previous section). The nett result is a decrease in other cost factors, e.g. maintenance, labour, waste disposal and overheads, due to the dilution of fixed costs and ultimately a decrease in the pre-reduction process overall production cost ($R/t \text{ FeCr}$).

Discounted cash flow (DCF) analysis

DCF analysis methods are capable of producing a good approximation of the value of a project in order to aid in the feasibility evaluation process. According to Hitch and Dipple (2012), it is fairly simple to appraise a project in terms of revenue versus cost, however, it is imperative to consider the time value of money and the influence that substantial up-front capital costs may have. Pšunder (2012) pointed out in a recent literature overview that the use of DCF methods for engineering project evaluation has increased significantly in the last decades. In appraising potential investments for its ability to quantify the added value to shareholders, financial analysis through DCF modeling are currently the most commonly used methodology (Hitch and Dipple, 2012). Pšunder and Ferlan (2007) further indicated that net present value

(NPV), net present value index (NPVI), internal rate of return (IRR) and modified internal rate of return (MIRR), were some of the most commonly used DCF methods, but that the most frequently applied were NPV and IRR methods. The employment of the IRR method is justifiable since it is easy to understand, due to the result being expressed in a percentage rate of return. Simultaneously, results can easily be compared between various projects and different forms of investments. The regular use of the NPV method can be justified by the simplicity of the calculation (Pšunder, 2012).

Assumptions

As indicated in the 'Process options' section, it is likely that current FeCr producers utilising the pre-reduction process would employ a rotary kiln for chromite pre-oxidation. The operation input parameters for the combined pre-oxidation and pre-reduction process (Figure 1) were obtained through personal communications with individuals from a large South African FeCr producer, applying the pelletised chromite pre-reduction process and from one of the co-author's personal experience in the FeCr industry, i.e. JP Beukes, whom held various senior positions in the FeCr industry in RSA. Capital costs were estimated by the General Works Project Manager responsible for the first and second phase development of the largest single-phase FeCr expansion in the world, with both phases employing the pre-reduction process (Henrico, 2014). The base case input parameters used in this study, based on costs estimated in 2015, are presented in Table I, II and III. In the cost modeling the chromite pre-oxidation process (Figure 1A) and pre-reduction process (Figure 1B) were kept as separate business units. Figure 4 presents a conceptual flow diagram of the financial model of the combined pre-oxidation and pre-reduction process (Figure 4A), indicating the effect of chromite pre-oxidation on SEC, lumpy carbonaceous reductants required for furnace smelting and FeCr production (additional FeCr produced), compared to the pre-

reduction process (Figure 4B). Revenue generated by the chromite pre-oxidation operation was divided into two income streams (Figure 4), I) pre-oxidised chromite sales and II) FeCr production increase revenue (returns as a result of the increase in FeCr production capacity). The pre-oxidised chromite sales price is determined from the cost distribution of the pre-reduction process (Figure 4). The furnace reductant and electricity cost factors per ton FeCr are reduced by utilising pre-oxidised chromite. The assumption was then made to keep the pre-reduction process production cost constant at R 10 000/t FeCr, which is the same as before exploiting oxidised ore. Therefore the pre-reduction process chromite ore cost factor is increased, which sets the pre-oxidised chromite sale price. Using pre-oxidised chromite also result in an increased production capacity. The profit generated by the additional FeCr produced served as the second income stream for the chromite pre-oxidation process.

Insert Figure 4

Insert Table I, II, III

Sensitivity analysis

Although it is important to correctly approximate the operation and cost parameters of the combined pre-oxidation and pre-reduction process, changes to these values will invariably take place due to economic fluctuation and advances in research and development. Therefore, sensitivity analysis is essential in determining the overall feasibility. A more comprehensive understanding of the project economics and viability

can only be achieved by evaluating the ranges between extreme levels for the various input parameters. Similar to Hitch and Dipple (2012), sensitivity analysis was first performed on the pre-oxidation process production cost model input parameters, since the pre-oxidation process production cost is subsequently required as a DCF input parameter. This allowed for the examination of deviations from the base case to assess the impact of the various input parameters. The sensitivity of each of these input parameters allowed for a more accurate appraisal of project value and return, as determined through DCF modeling and its corresponding sensitivity analysis.

Financial modelling results and discussion

Base case results

The base case results, consisting of the pre-oxidised chromite cost margins, the cost distributions of the pre-reduction process with and without pre-oxidised chromite, and the DCF model outputs are listed in Table IV. In order to keep the production cost of the pre-reduction process constant at R 10 000/t FeCr as explained in the 'Assumptions' section, the pre-oxidised chromite sales price was determined at R 905.28/t OC. By employing the pre-oxidation process and utilising pre-oxidised chromite the cost distributions of furnace electricity and reductants was reduced from 17.76% and 6.87%, to 16.43% and 6.04%, respectively. By applying the method used by Kleynhans et al. (2012) to convert electrical energy improvements to financial gains, the reduction in the furnace electricity cost distribution translated to ~ R 48.5 million/a for the 364 000 t/a pre-reduction process. The financial gain associated with the decrease of the furnace reductant cost distribution by using Figure 2 translate to ~ R 30 million/a for the 364 000 t/a pre-reduction process. It is thus evident that applying this process has financial advantages.

Insert Table IV

Although not investigated in this study, another cost benefit resulting from employing the pre-oxidation process is the dilution of fixed costs. The large increase in production capacity effectively ensures a reduced impact of fixed cost with the fixed cost only increasing slightly. For a pre-oxidised chromite production cost of R 893.01/t OC and a FeCr production increase of 29 523 t FeCr/a, the DCF model yielded a NPV of ~R 895 million with an IRR of 30.5% and a profitability index (PI) of 2.88 after tax. This significantly positive base case NPV, the IRR approximately three times greater than the 10% discount rate and PI approximately 3 times higher than one suggests that integrating the pre-oxidation process and utilising pre-oxidised ore may be a potentially feasible development option from a project economics standpoint. In order to put these results into perspective, it would be beneficial to compare the NPV and IRR to other reasonable values within the industry. However, economic feasibility results of smaller expansion or process improvement projects are not readily available in the peer reviewed scientific domain, since publication of such results could potentially erode the strategic advantage of the developing comparing. Development of The Ring of Fire, a large mineral resource-rich area of approximately 5 120 km² located in Canada's Northern Ontario region can be considered as a recent example. Based on current projections, the chromite deposit is significant enough to sustain North American activity for a century (OCC, 2014). KWG Resources of Montreal, Canada released the preliminary economic assessment (PEA) study for the Big Daddy chromite deposit in the Ring of Fire in 2011. The PEA examined an open pit mine, crushing plant, site

infrastructure as well as development of a railway and power line to the site. Pre-production capital expenses was estimated to be around \$784 million which included half of the \$900-million cost of the railway to establish an 8 000 t/d operation over a 16-year life cycle. At a 2011 exchange rate of ~7 ZAR/US\$, capital cost to develop the Big Daddy chromite deposit amounts to ~ZAR 5.5 billion. The Big Daddy projects undiscounted gross revenue was appraised at ~\$12.6 billion. The after-tax evaluation estimated the NPV to be ~\$1.6 billion at an 8% discount rate or ~\$1.25 billion at 10% discount rate. The after-tax internal rate of return calculated to ~31.8%, resulting in a pre-tax payback period of 2.5 years (CMJ, 2011; KWG Resources, 2011).

Although the NPV and IRR looks promising and shows comparisons with the PEA study for the Big Daddy chromite deposit, it is necessary to keep in mind that this investigation is conceptual in nature and that an inherent uncertainty surrounding some model input parameters exist to a certain extent. Intrinsically, sensitivity analysis allowed for a more in-depth investigation into the influences of some uncertainties on the overall project appraisal, which are discussed in the following sections.

Cost sensitivity of the pre-oxidation process in isolation

The overall sensitivity of the pre-oxidation process's pre-oxidised chromite production cost parameters, consisting of a spider plot diagram showing parameter sensitivity and a table ranking these parameters from most to least sensitive, are presented in Figure 5. The spider plot offers a comparative representation of the sensitivity of the pre-oxidised chromite production cost model elements. Input elements with the sharpest gradients represent the parameters with the greatest impact per unit of change from the base case, as denoted by the x-axis with the base case value set at 0%.

Insert Figure 5

The most sensitive parameter defined through sensitivity analysis, if the pre-oxidised chromite process' production cost was considered in isolation, was chromite ore cost. This is easily explained since (i) the pre-oxidation process section was considered as a separate economic component in the financial cost model to determine the oxidised chromite production cost and selling price, and (ii) ~90.5% of the total pre-oxidised chromite production cost is allocated to the cost of obtaining chromite ore. PF cost and PF composition was jointly the second most sensitive parameters. The cost of PF account for ~7.3% of the total pre-oxidised chromite production cost. The percentage change from the base case for the PF composition in Figure 5 is only indicated as a negative change, which can be attributed to the kiln being operated only on PF in the base case scenario. The cost contribution of the PF to the total chromite pre-oxidising production cost can, however, be significantly reduced if a mixture of PF and CO off-gas, or exclusively CO from the closed SAF, can be used. The use of CO off-gas in the pre-reduction kiln is not completely effective, since temperatures higher than 1250 °C are required. Although the adiabatic flame temperature of CO gas is high enough (du Preez et al., 2015, Niemelä et al., 2004) it has been found in practice that PF fuel has a deeper penetrating flame. Pre-reduction kilns are also long (60-80 m) to ensure the required retention time of ~3 hours for effective pre-reduction. Consequently, the fuel utilised need to be able to penetrate deep into the kiln for effective heat transfer and to maximise the area with a temperature distribution higher than 1250 °C. It will, however, be possible to use CO off-gas in the chromite pre-oxidation process since a lower temperature (1000 °C) and shorter retention time (1 hour) are required that implies a shorter kiln. The remaining pre-oxidised chromite

production cost parameters account for less than 2.2% of the total production cost, thus in terms of sensitivity these parameters had minimal impact.

The pre-reduction level was also considered since it has an impact on the pre-oxidised chromite required for the pre-reduction process. If the pre-reduction level decreases from the base case, the FeCr production capacity also decreases, resulting in a decrease of pre-oxidised chromite required. This will result in an increase in the production cost per ton of pre-oxidised chromite produced. The opposite would occur if the pre-reduction level increases. However, the sensitivity of the pre-reduction level was minimal, since it is approximately a hundred and thirty times less sensitive than chromite cost.

Cost sensitivity of the pre-oxidation process integrated with the pelletised pre-reduction process

Spider plot diagrams showing parameter sensitivity relating to the NPV and IRR with these parameters being ranked from most to least sensitive in a table are presented in Figure 6 in order to illustrate the overall sensitivity of the DCF model designed for the integrated pre-oxidation and pre-reduction process.

Insert Figure 6

Although the level of pre-reduction was relatively insensitive with regard to the pre-oxidation process's production cost, it was found to be the most sensitive parameter in determining both the NPV and IRR. The level of pre-reduction, accounting for

~34.9% of the overall DCF sensitivity, is approximately two times more sensitive than the parameter ranked second for both the NPV and IRR. The level of pre-reduction primarily affects the FeCr production capacity which in turn has an effect on the pre-oxidised chromite required. As a result the level of pre-reduction has an effect on both the chromite pre-oxidation processes revenue streams (Figure 4) and consequently impacts the operations cash flow. Chromite cost, the second most sensitive parameter, accounted for ~18.3% of the overall DCF sensitivity. Four parameter, more specifically the benefit escalation factor, FeCr Cr content, FeCr price and cost escalation factor, could be group together for each accounting between ~9-12% of the overall DCF sensitivity. An interesting observation is that the order of importance for these four parameters were dissimilar for the NPV and IRR. Nevertheless, these cost or price parameters has significant implications for overall project feasibility by directly controlling the total available revenue from the two income streams. Specifically, significant increases in the cost of chromite and parameters negatively influencing the FeCr price and income thereof will imply that there will not be an adequate source of revenue in order to offset the associated costs. It is interesting to note that the total capital cost is the seventh most sensitive parameter for the IRR and the eight most sensitive for NPV. It was originally assumed that the capital cost would have a bigger influence on project appraisal as a result of the front-loaded nature of the cash flows. However, it does not have a considerable impact on project valuation. The capital cost necessary for funding may have a more dramatic impact on the ability to secure project financing, either through debt or equity. Although this does not necessarily impact project valuation, it may have an impact on project feasibility in determining the ability to generate funding for project construction. Factors of less significant influence include the discount rate, income tax rate, project contingencies, decommissioning cost,

freight- and development cost. The significance and contribution of each of the individual parameters investigated through this research cannot be ignored. However, their ranking in terms of sensitivity has provided a means by which further research can be prioritised and efforts can be focussed on parameters that will results in the greatest influence on project valuation.

Conclusions

It was recently proven that pre-oxidation of fine chromite ore, prior to pelletised pre-reduction, significantly decrease the SEC and lumpy carbonaceous reductants required for furnace smelting. In this paper an analysis of the techno-economic feasibility of integrating chromite pre-oxidation into the currently applied pelletised pre-reduction process as a pre-treatment method was presented. RSA's FeCr industry provided the ideal backdrop conditions within which the techno-economic feasibility of implementing such a chromite pre-oxidation process could be evaluated. Through conceptualisation of the pre-oxidation process route it became evident that FeCr producers currently utilising the pre-reduction process would most likely opt to employ an operation with a rotary kiln at its core to conduct chromite pre-oxidation. Chromite pre-oxidation at the optimum temperature of 1000 °C translated to an ~8.5% increase in the level of achievable chromite pre-reduction (from ~46.5% to ~55.5%), a ~8.3% improvement in the SEC (from ~2.4 to ~2.2 MWh/t) and a ~14% decrease (from ~99.5 to ~85.5 kg/t pellets) in the amount of lumpy carbonaceous material required during SAF smelting. In order to more accurately approximate input costs for further lifecycle financial modelling, a comprehensive estimate of the costs associated with pre-oxidising the fine chromite ore was determined. The lifecycle financial model, which was built on a DCF approach, generated a base case NPV of ~R895 million and an IRR of ~30.5% after tax. This strongly indicates that integration of the chromite pre-oxidation

process into the currently applied pre-reduction process may be viable from a financial perspective. Sensitivity analysis of the pre-oxidation process in isolation indicated that the most influential parameter was chromite ore cost, whereas the most influential parameter was found to be the level of pre-reduction if the pre-oxidation process was integrated with the pelletised pre-reduction process. The level of achievable pre-reduction is interrelated to the pre-oxidation temperature, which implies that the capability of maintaining the optimum pre-oxidation temperature is of critical importance.

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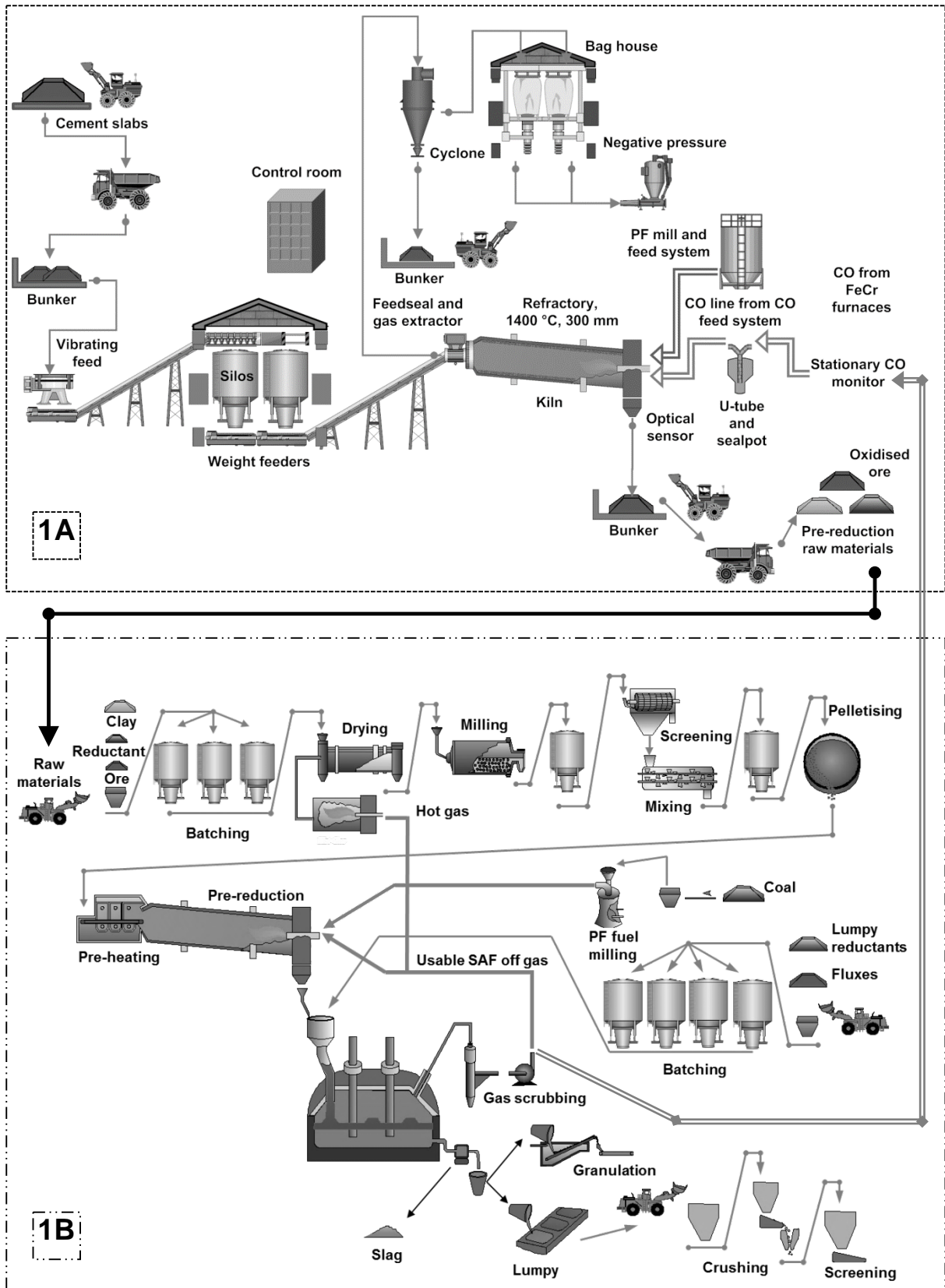


Figure 1-(A) Pre-oxidation process, (B) Pre-reduction process

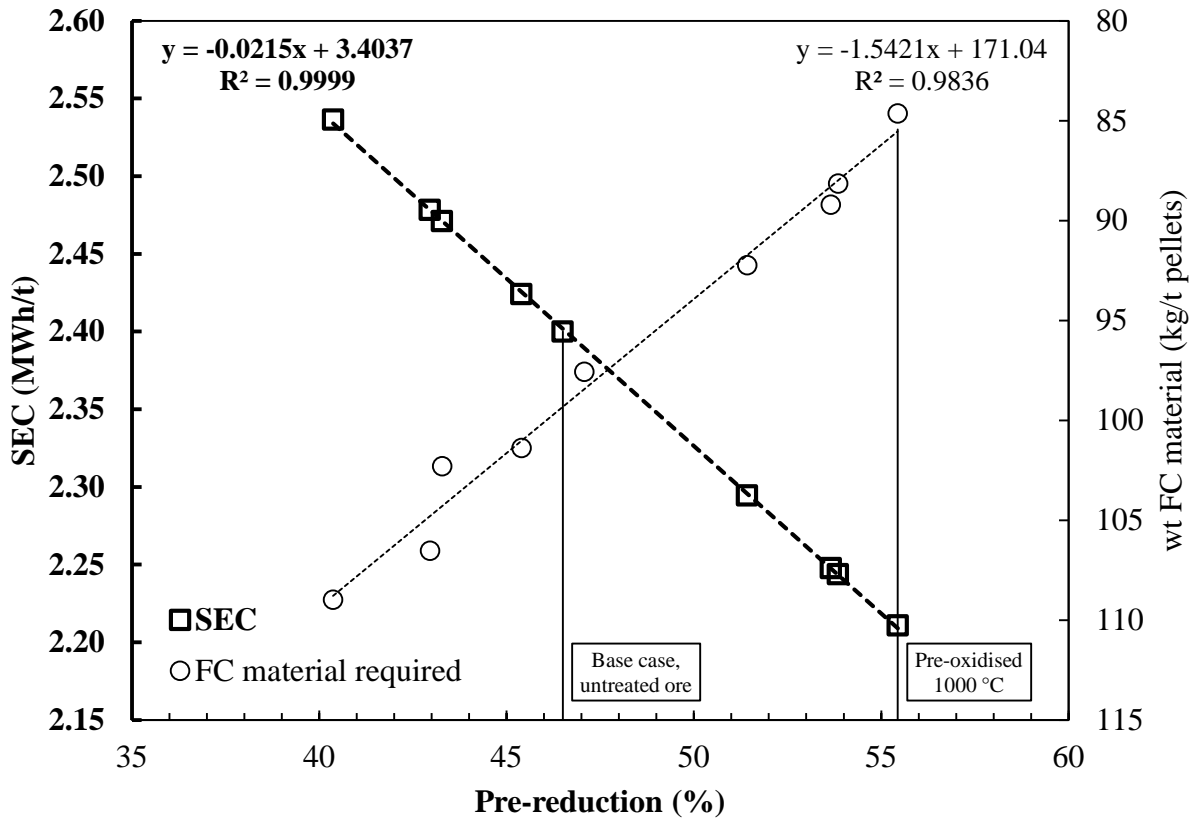


Figure 2-The effect of enhanced pre-reduction by utilising pre-oxidised fine chromite ore (x-axis) on the SEC (primary y-axis), as well as on the weight (wt) FC required per ton pre-reduced pellets (kg/t pellets) (secondary y-axis) (Kleynhans et al., 2015)

Combined pre-oxidation and pre-reduction process

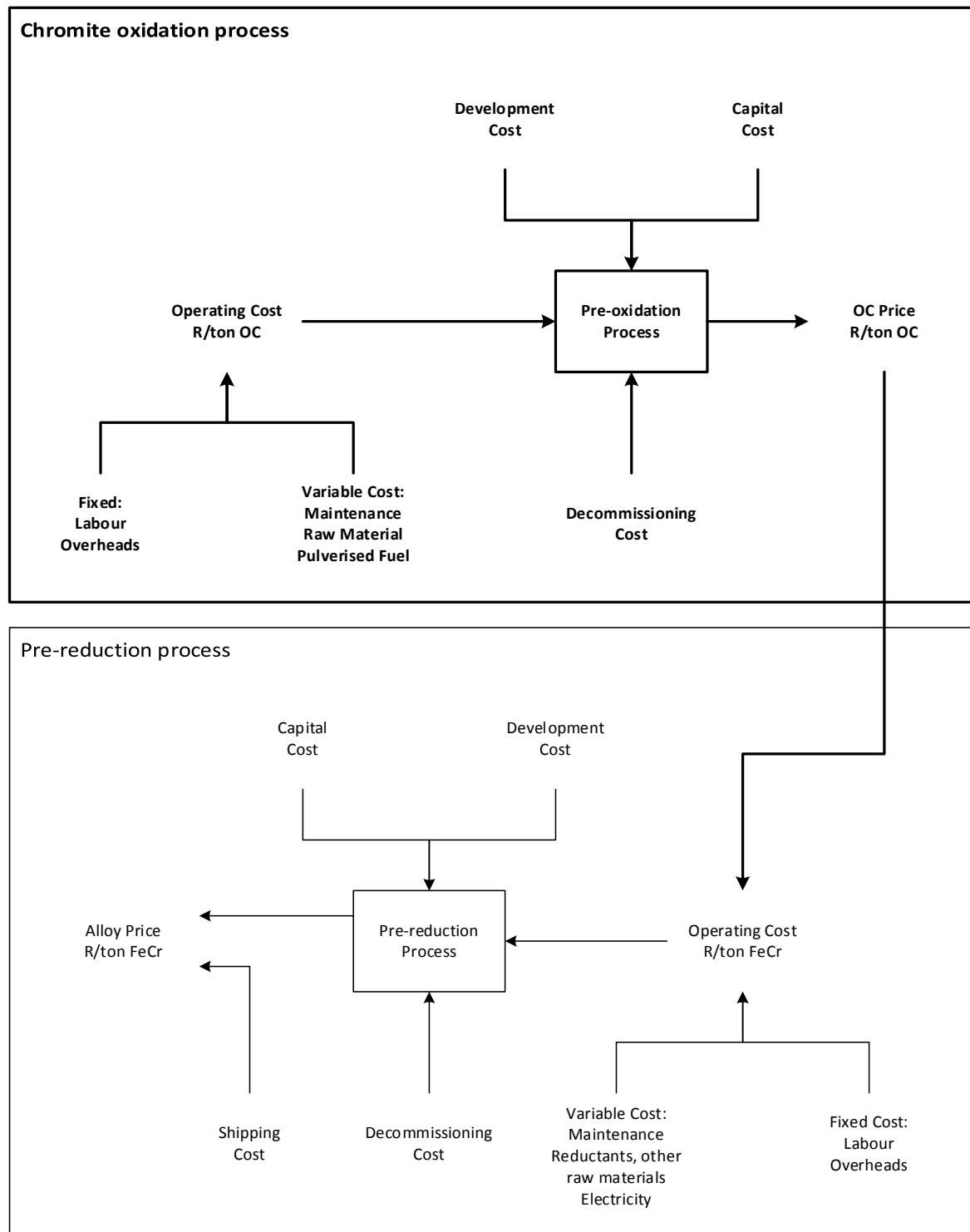


Figure 3-Life cycle cost factor breakdown of the chromite pre-oxidation process and in combination with the pre-reduction process

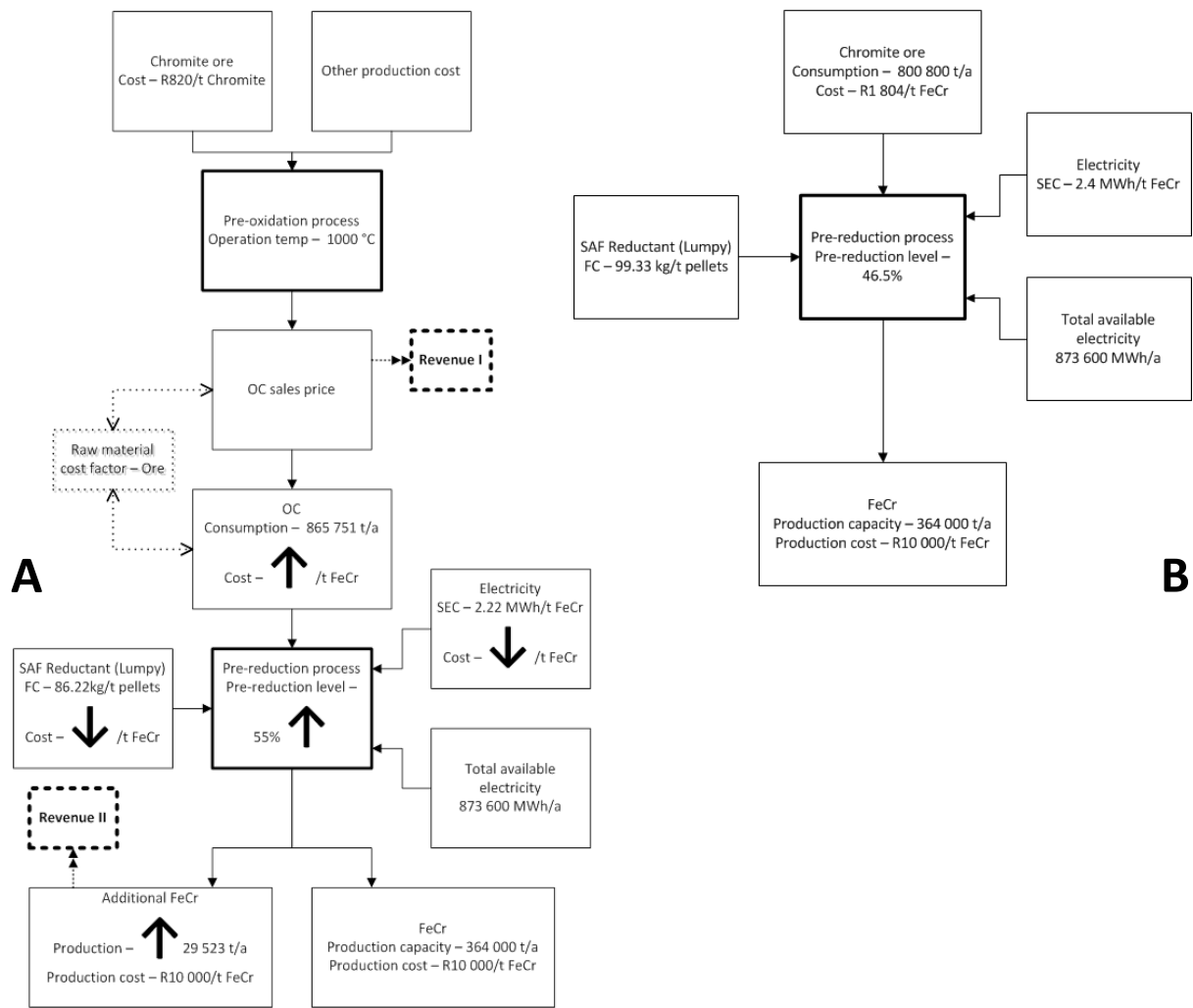
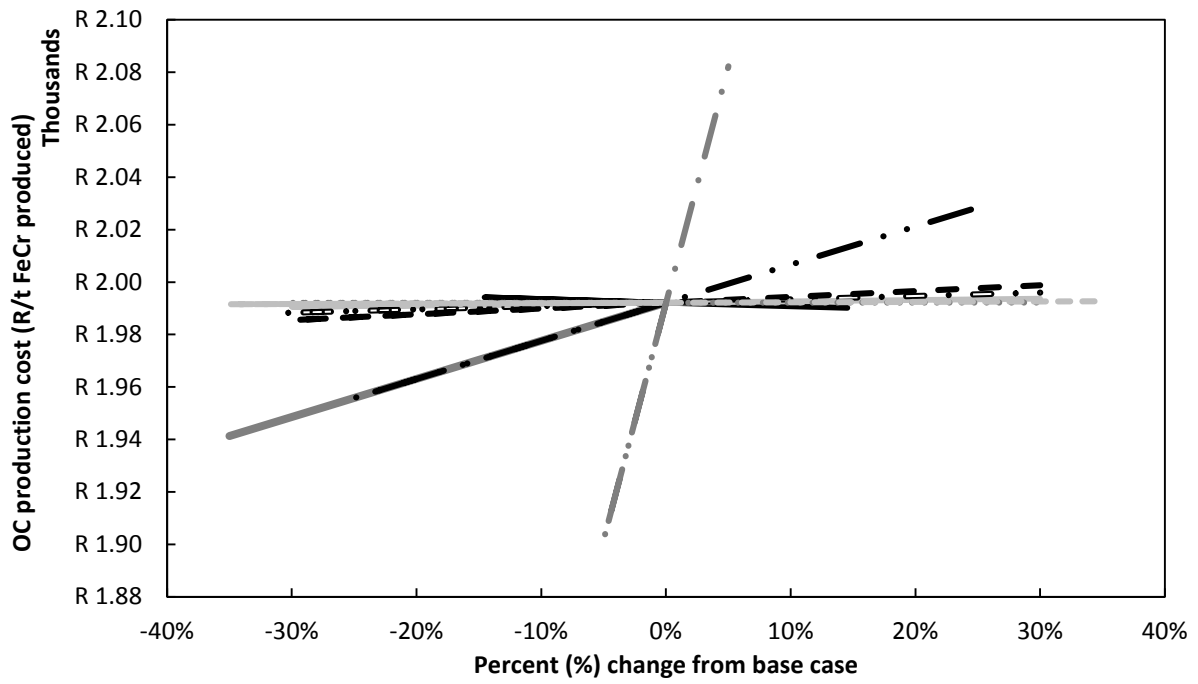
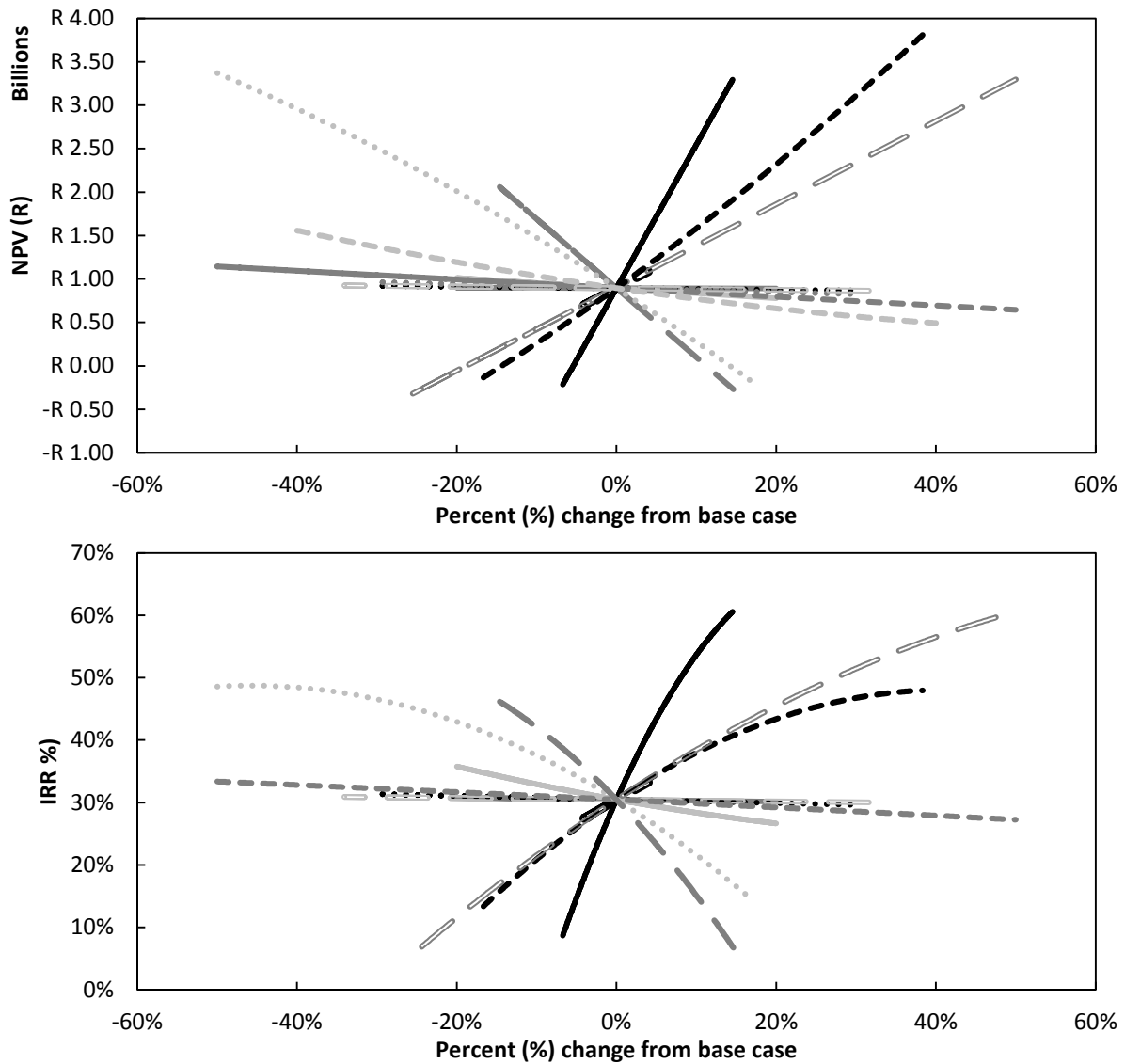


Figure 4-Conceptual flow diagram of the financial model for the combined pre-oxidation and pre-reduction process (A), indicating the influence of chromite pre-oxidation on SEC, lumpy carbonaceous reductants required for furnace smelting and FeCr production (additional FeCr produced), the determination of the OC sales price and the pre-oxidation process revenue streams (I and II), compared to the pre-reduction process (B)



Parameter	Rank
Chromite cost	1
PF Cost	2
PF composition	2
Internal transport	3
Pre-reduction level	4
Maintenance	5
Labour	6
Auxiliary power	7
Refractory	8

Figure 5-Overall sensitivity of pre-oxidised chromite production cost parameters



Parameter	Rank		Overall DCF sensitivity (%)
	NPV	IRR	
Pre-reduction level	1	1	34.86
Chromite cost	2	2	18.33
Benefit escalation factor	3	5	11.90
FeCr Cr content	6	3	10.26
FeCr price	5	4	10.21
Cost escalation factor	4	6	8.90
Total capital cost	8	7	2.33
Discount Rate	7	-	1.35
Income tax rate	9	8	0.97
Project contingencies	12	9	0.31
Decommissioning Cost	10	-	0.23
Freight cost	11	11	0.20
Development cost	13	10	0.14

Figure 6-Overall sensitivity of the DCF model

Table I

Base case model input parameters (based on costs estimated in 2015)

Input parameters	Value	Unit
Process availability	90	%/a
Available hours	7 884	h
Furnace capacity	63	MVA
Furnaces	2	-
Power Factor	0.879	-
Total available electricity	873 600 000	kWh/a
Electricity price	0.74	R/kWh
ZAR/US\$ exchange rate	10.95	ZAR/US\$
Freight cost* (Wellmer et al., 2008)	25	US\$/t FeCr
FeCr price (Merafe-Resources, 2014)	1.19	US\$/lb Cr contained
Cr content in FeCr produced	50	%
Coke price (Biermann et al., 2012)	4 000	ZAR/t
Anthracite price (Biermann et al., 2012)	1 100	ZAR/t
Char price (Biermann et al., 2012)	900	ZAR/t
<i>*Shipping distance of ~8 300 nmi</i>		
Furnace reductant mixture composition:		
Furnace reductant FC content	77.8	wt%
Coke	30	%
Anthracite	20	%
Char	50	%
Pre-reduction pellet composition:		
Chromite/OC	76.5	wt%
Reductant	20.0	wt%
Reductant FC content	75.0	wt%
Clay binder	3.50	wt%
Pre-reduction process (with un-oxidised chromite):		
FeCr production capacity	364 000	t FeCr/a
Chromite consumption	2.2	t Chromite/t FeCr
Pre-reduction process pellet consumption	2.876	t Pellets/t FeCr
Pre-reduction level	46.50	%
Production cost	10 000.00	R/t FeCr
Combined pre-oxidation & pre-reduction process:		
Pre-reduction increase	8.50	%
SEC	2 220	kWh/t FeCr
Kiln burner fuel composition	100	% PF
OC kiln PF consumption	0.0627	t PF/t OC
FeCr production capacity	393 523	t FeCr/a
Chromite required	865 751	t Chromite/a
OC production	1.014	t OC/t chromite
OC consumption	2.231	t OC/t FeCr
OC produced	877 872	t OC/a
OC Pre-reduction pellet consumption	2.916	t OC Pellets/t FeCr
OC Pre-reduction pellets required	1 147 545	t OC Pellets/a

<i>Table II</i>			
Base case pre-oxidised chromite ore production costs (based on costs estimated in 2015)			
Fixed costs	Quantity	Unit cost	Cost/t OC produced
Operators	4	R 240 000.00	R 1.09
Maintenance personnel	2	R 540 000.00	R 1.23
PPE	6	R 250.00	R 0.0017
Total			R 2.33
Variable costs	Value	Unit	Cost/t OC produced
Internal transport (Moving)	700.00	R/h	R 6.29
Internal transport (Loading)	400.00	R/h	R 3.59
Maintenance	5.70	R/t OC	R 5.70
Refractory	0.10	R/t OC	R 0.10
PF	1 038.00	R/t PF	R 65.08
Auxiliary power	0.68	R/t OC	R 0.68
Provident fund for large replacements	0.57	R/t OC	R 0.57
Chromite ore	820.00	R/t Chromite	R 808.68
Total			R 890.69
Grand Total			R 893.01

*Table III***Base case DCF model input parameters (based on costs estimated in 2015)**

Input parameters	Value	Unit
Development phase duration	1	years
Development cost	5	% of total capital cost
Construction phase duration	2	years
Total capital cost:	383 627 322	R
Civils	71 232 000.00	R
Structural	25 446 400.00	R
Plate work	14 660 800.00	R
Mechanical	188 182 400.00	R
Electrical	32 947 376.00	R
Geotechnical studies	1 120 000.00	R
Project contingencies	15	% of capital cost
Plant Life	20	years
Depreciation	5 year MACRS	
Decommissioning phase duration	2	years
Decommissioning Cost	15	% of total capital cost
Cost escalation factor (Inflation rate)	6	%
Benefit escalation factor (FeCr price increase)	6	%
Income tax rate	28	%
Discount rate	10	%

<i>Table IV</i>				
Base case results				
Parameter	Value	Unit		
<i>Oxidised chromite production</i>				
Oxidised chromite production cost	893.01	R/t OC		
Oxidised chromite price	905.28	R/t OC		
FeCr production increase	29 523	t FeCr/a		
<i>Cost distribution</i>				
Production cost (PR process)	10 000.00	R/t FeCr		
<i>PR process using chromite</i>			<i>% of production cost</i>	
Chromite ore	1 804.00	R/t FeCr	18.04	
Electricity	1 776.00	R/t FeCr	17.76	
Furnace reductants	686.62	R/t FeCr	6.87	
Other production costs	5 733.38	R/t FeCr	57.33	
<i>PR process using OC</i>			<i>% of production cost</i>	
OC ore	2 019.50	R/t FeCr	20.20	↑
Electricity	1 642.76	R/t FeCr	16.43	↓
Furnace reductants	604.35	R/t FeCr	6.04	↓
Other production costs	5 733.38	R/t FeCr	57.33	-
NPV (after tax)	R 894 489 279.24			
IRR (after tax)	30.5%			
Profitability Index (after tax)	2.88			
Simple Payback	3 years 0 months 16 days			
Discounted Payback	4 years 0 months 11 days			

CHAPTER 5: PROJECT EVALUATION

The success of a project is mostly determined by the number of objectives successfully achieved. In this chapter, the results of the article are put into perspective in § 5.1. In § 5.2 the project is evaluated against the objectives set in §1.2. Some future perspectives are presented in § 5.3, while the chapter concludes with some final remarks in § 5.4.

5.1 Results substantiation

Although the results presented in Chapter 4 indicated that integration of the chromite pre-oxidation process into the currently applied pre-reduction process may be techno-economically feasible, it is important to put these results into perspective.

Xstrata Alloys, now Glencore Alloys, took the decision in 2003 to develop Phase 1 of its Lion FeCr smelter complex near Steelpoort in the Mpumalanga province of RSA. The capital committed to the smelter facility was approximately ZAR 1.44 billion, which excluded ~R230 million for the concurrent development of the Helena mine that forms part of Glencore's Thorncliffe mining complex. The bulk earthworks were completed in October 2004, construction began around November 2005 and Phase 1 was completed in September 2006. The Phase 1 smelter operation utilising Glencore's Premus technology (known scientifically as pelletised chromite pre-reduction) consists of two 63 MVA closed SAFs and has a production capacity of ~360 000 t/a. Production costs is estimated to have been between ZAR 3 000 and ZAR 5 000/t FeCr excluding shipping costs to clients in 2006/2007. The Phase 2 expansion of the Lion FeCr complex was developed at a total capital cost of approximately ZAR 4.9 billion, which included ~ZAR 700 million for the concurrent development of the 1.2 million MT/a Magareng mine within the Thorncliffe mine complex. Construction began in the first quarter of 2011 and Phase 2 was finally commissioned in May 2014, doubling the 360 000 t/a capacity of Phase 1 to give the Lion FeCr smelter complex a combined production capacity of 720 000 t/a. Production costs at the time is estimated to have been between ZAR 7 000 and ZAR 10 000/t FeCr excluding shipping costs to clients in 2014/2015. Xstrata Alloys carried out the work in-house for the development of Phase 1, as a costing exercise on adopting the turnkey project

route showed that running the project internally would result in savings of between ZAR 400 million to ZAR 700 million. This approach was, however, not followed for the development of Phase 2.

It would have been beneficial to compare the NPV and IRR of these two projects with the results generated by this study; however these values are not available in the public domain as far as the authors could assess. Although the IRR and NPV of Phase 1 and 2 of the Lion FeCr complex could be determined similarly, it is beyond the scope of this investigation. There are, however, some comparisons that can be made. The additional FeCr produced, ~30 000 t/a, by applying the pre-oxidation process is approximately 12 times less than the production capacity of one of the Lion FeCr complexes phases. Interestingly, the capital required to implement the pre-oxidation process (~ZAR 380 million) is also approximately 12 times less than the capital to develop Phase 2 of the Lion FeCr complex (Lanham, 2005; Anon, 2006; Creamer, 2010; E&MJ News, 2011; Creamer, 2014; Rayn, 2014).

Another similar project to compare this study to would be the construction of a metal recovery plant to reclaim FeCr from the slag produced from smelting. ASA Metals near Dilokong in the Mpumalanga province of RSA finished construction of a metal recovery plant in 2007 (Davenport, 2006). The plant was constructed at a capital cost of ~ZAR 30 million. At the time (2007), ASA Metals produced ~120 000 t FeCr/a at the facility, generation ~180 000 t Slag/a. According to ASA Metals the slag, resulting from FeCr production at their operation, normally contains between 2.5% and 3.5% FeCr. This translates to approximately 4500 to 6300 t/a recoverable FeCr. Considering a capital cost escalation similar to the escalation between Phase 1 and Phase 2 of the Lion FeCr complex, the capital cost to construct the same metal recovery plant can be estimated at ~ZAR 70 million. The FeCr reclaimed from the slag by the metal recovery plant is thus approximately 4.7 to 6.7 times less than the additional FeCr produced, ~30 000 t/a, by applying the pre-oxidation process. The capital required to implement the pre-oxidation process (~ZAR 380 million) is approximately 5.5 times less than the capital to construct the metal recovery plant (~ZAR 70 million). The payback period for this project was ~6 months (du Toit, 2012); however this could have been influenced by the sharp increase in FeCr prices during 2007 and 2008 (Figure 2–6). Nevertheless, it is still comparable to the relatively short payback period of the chromite pre-oxidation process, i.e. 1.7 years.

The Ring of Fire, a large mineral resource-rich area of approximately 5 120 km², is located in Canada’s Northern Ontario region approximately 540 km northeast of Thunder Bay and roughly 330 km from the nearest road or rail line in Nakina (approximately 250 km from Thunder Bay). Since the early 2000s, significant deposits of copper, zinc, nickel, platinum, vanadium, and gold have been found in the region. The most promising discovery is the first commercial quantities of chromite in North America (OCC, 2014). A map of northern Ontario, showing the remote, infrastructure-poor area where these chromite deposits are situated, is presented in Figure 5–1 (KWG Resources, 2011). Based on current projections, the deposit is significant enough to sustain activity for a century.

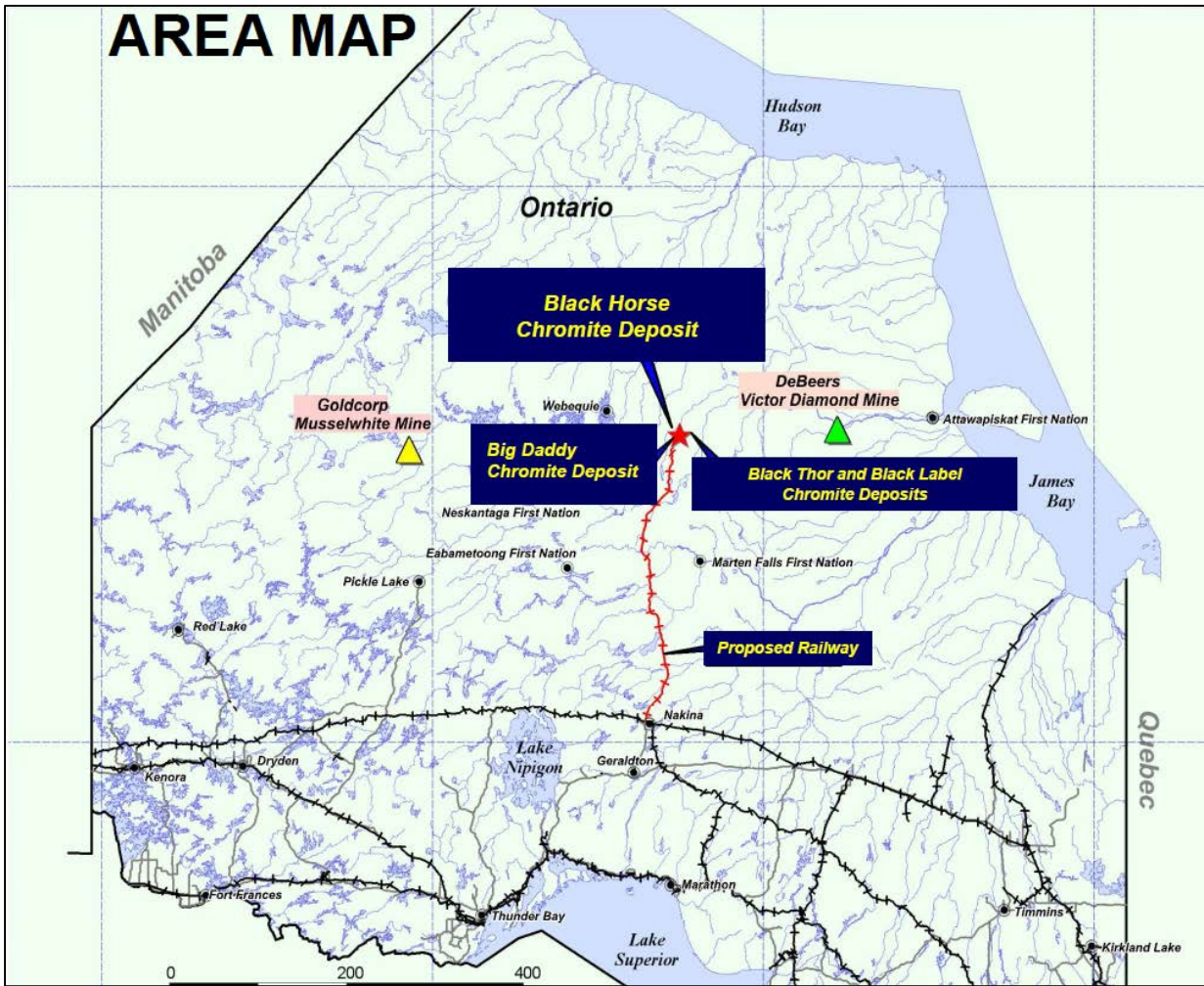


Figure 5–1: A map of northern Ontario, showing the remote, infrastructure-poor area where The Ring of Fire chromite deposits are situated (KWG Resources, 2011).

KWG Resources of Montreal, Canada released the preliminary economic assessment (PEA) study for the Big Daddy chromite deposit in the Ring of Fire in 2011. The PEA examined an

open pit mine, crushing plant, site infrastructure as well as development of a railway and power line to the site. Pre-production capital expenses was estimated to be around \$784 million which included half of the \$900-million cost of the railway to establish an 8 000 t/d operation over a 16-year life cycle. The Big Daddy projects gross revenue was appraised at ~\$12.6 billion. The pre-tax evaluation estimated the NPV to be ~\$2.5 billion at an 8% discount rate or ~\$2.0 billion at 10% discount rate. The internal rate of return calculated to ~42.0%, resulting in a payback period of 2.5 years (CMJ, 2011; KWG Resources, 2011). At a 2011 exchange rate of ~7 ZAR/US\$, capital cost to develop the Big Daddy chromite deposit amounts to ~ZAR 5.5 billion. It is important to note that this capital cost only covers the development of the mine, which is an order of magnitude larger than that of the capital costs allocated to mine development in the previously mentioned Lion projects.

By comparing the techno-feasibility results (Chapter 4) to projects that are already operationally successful on a commercial scale as well as projects currently under feasibility investigation, a greater understanding in terms of the viability of integrating the chromite pre-oxidation process into the currently applied pre-reduction process was obtained. The assessment strengthens the articles conclusion that the base case results strongly indicate that integration of the chromite pre-oxidation process into the currently applied pelletised pre-reduction process may be viable from a financial perspective.

5.2 Project evaluation

The project was evaluated using the objectives set in Chapter 1. The points listed below therefore correlate with the objectives set in Section 1.2.

- (i) A concise and relevant literature survey was conducted (Chapter 2). The importance of RSA's FeCr industry was justified in terms of chromite resources (Section 2.1.1) and FeCr production (Section 2.1.5). Factors influencing this industry were discussed in the light of economic and market considerations (Section 2.1.2), with two of these factors, carbonaceous reductants (Section 2.1.3) and electricity supply (Section 2.1.4), highlighted separately. From the main processes and techniques discussed in Section 2.2 it was evident that, although various processes are utilised for the production of FeCr, pre-reduction seem to be the most viable option to reduce a FeCr smelter plant's SEC. Chromite pre-reduction was found to be a well-established practice in the South African

FeCr production industry (Section 2.3.1). The use thereof poses numerous advantages for FeCr producers (Section 2.3.2). The fundamental aspects surrounding chromite pre-reduction was highlighted in Section 2.3.3. Although this study focused on the techno-economic aspects of the pre-oxidation process, limited information was available in the public domain on chromite pre-oxidation. Therefore Chapter 3 was included as an extension of the literature survey, but specifically focussed on pre-oxidation prior to milling, agglomeration and pre-reduction. The effects of pre-oxidation on the micro- and crystalline structure of chromite, as well as on chromite pre-reduction were presented in. The effects discussed in Sections 3.1-3.4 was contextualise in Section 3.5 from a theoretical thermochemical perspective. The energy implications resulting from pre-reduction alterations due to the utilisation of pre-oxidised ore were discussed in Section 3.6. The effect of pre-oxidation on the mechanical strength and thermomechanical behaviour of pre-reduction pellets was discussed in Sections 3.7 and 3.8, respectively. From a health and safety perspective it is important to quantified the amount of Cr(VI) that could be formed if chromite ore is pre-oxidised, which was investigated in Section 3.9.

- (ii) By investigating process approaches to conduct pre-oxidation of chromite prior to pre-reduction (Chapter 4) the conclusion was made that FeCr producers already utilising the pre-reduction process would most-likely employ a counter-current rotary kiln for this purpose. FeCr producers using chromite pre-reduction are accustomed to kiln operation and would prefer this route as it fits within their current pre-reduction operations culture. It also has an advantage from a maintenance perspective, i.e. employing a kiln with the same diameter for pre-oxidation as the kiln used for pre-reduction.
- (iii) The techno-economic feasibility of integrating a pre-oxidative process with a smelter operation applying the pelletised chromite pre-reduction was evaluated successfully (Chapter 4). The base case NPV and IRR indicated that the project could be feasible from a financial perspective.
- (iv) Sensitivity analyses were successfully performed on the financial model. Sensitivity analysis of the pre-oxidation process in isolation indicated that the most influential operational parameter was chromite ore cost, whereas the most influential parameter was found to be the level of pre-reduction if the pre-oxidation process was integrated with the pelletised pre-reduction process. The level of achievable pre-reduction is

interrelated to the pre-oxidation temperature, which implies that the capability of maintaining the optimum pre-oxidation temperature is of critical importance.

- (v) The final objective concerning recommendations with regard to future perspectives is discussed in Section 5.3

5.3 Future perspectives

Although integration of the chromite pre-oxidation process into the currently applied pre-reduction process shows potential, pre-oxidation could also be considered as a pre-treatment process prior to other FeCr production processes. The process that could greatly benefit from the pre-oxidation of ore would be DCF operations (Figure 2–11, Option D). The DC arc process allows the direct use of chromite fines (< 6mm, 90% < 1mm) without the need for expensive agglomeration techniques (pelletising). Furthermore, non-coking coal can be used as reduction agent, which is low-priced compared to metallurgical coke. The main disadvantage of DCF operations is the relatively high SEC, i.e. ~4.5-4.8 MWh/t FeCr, compared to conventional SAF operations (3.9–4.2 MWh/t FeCr), the oxidative sintered process (>3.1 MWh/t FeCr) and the pre-reduction process (~2.4 MWh/t FeCr). However, in order to assess the techno-economic feasibility of pre-oxidation prior to DC arc smelting, the effect of pre-oxidation on DCF SEC needs to be determined. Another crucial future perspective would be the development of a method to determine the extent of pre-oxidation, similar to determining the level of pre-reduction achieve. This would be important in order to assess the effect of pre-oxidation on DCF SEC. Companies follow different approaches during the lifecycle development of a project. Although the author (the candidate) recommends that the project be tested on pilot scale, it is more-likely that FeCr producers would prefer to conduct a campaign study on a commercial scale.

5.4 Final remarks

In conclusion, the author (the candidate) would like to assess this MEng (Option B) dissertation using the outcomes prescribe for a Magister in Ingeniaria degree by the NWU. In short, the programme outcomes, to which an MEng (Option B) dissertation should comply, will have been achieved if it is demonstrated that:

The candidate is competent in applying research methodology or advanced design and/or investigative skills as evidenced by a dissertation with proper structure, style and language that includes:

- Identification of the research or engineering problem and formulation of objectives for the study.
- A concise and relevant literature survey.
- Development of the necessary research or design/investigative procedures and experimental facilities/numerical models.
- Execution of a comprehensive design or investigation to address the problem.
- Verification of the results.
- Assessment of the results.
- Conclusions.

From the candidate's point of view these outcomes were successfully achieved. Additionally a meaningful contribution was made to the South African FeCr industry. As the true measure of scientific research is the acknowledgment of the work by peers, the candidate intends on publishing the results obtained and already submitted the article to a peer reviewed accredited journal recognised by Thomson ISI (formally the Institute for Scientific Information) and the South African Department of Education and Training (DET). Since it is not required at Masters level to make a significantly new scientific contribution, the abovementioned contribution can therefore be regarded as sufficient proof that this study surpassed the requirements of an MEng.

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Evaluation of an investment project – commercial profitability

Introduction

Commercial profitability analysis is the first step in the economic appraisal of a project. It is concerned with assessing the feasibility of a new project from the point of view of its financial results. The project's direct benefits and costs are, therefore, calculated in pecuniary terms at the prevailing (expected) market prices. This analysis is applied to appraise the soundness and acceptability of a single project as well as to rank projects on the basis of their profitability. The commercial profitability analysis comprises:

- Investment profitability analysis
- Financial analysis

The two types of analyses are complementary and not substitutable. Both must be carried out since they are concerned with different aspects of an investment proposal. Investment profitability analysis is the measurement of the profitability of the resources put into a project, more directly the return on the capital no matter what the sources of financing. Thus, investment profitability analysis is an assessment of the potential earning power of the resources committed to a project without taking into account the financial transactions occurring during the project's life. On the other hand, financial analysis has to take into consideration the financial features of a project to ensure that the disposable finances shall permit the smooth implementation and operation of the project.

Different methods may be used as a basis on which to assess the investment profitability of a project:

- Simple rate of return
- Pay-back period
- Net present value
- Internal rate of return

The first two methods, the simple rate of return and the pay-back period, are usually referred to as the simple or static methods since they do not take into consideration the whole life span of the project but rely on one model period (most frequently one year) or at best on a few periods. Furthermore, their application is based on the project's annual data, meaning that all the inflows and outflows enter the analysis at their nominal non-discounted values as they appear at a given time during the project's life.

The net present value and internal rate of return are called discounted or dynamic methods because they take into consideration the entire life of a project and the time factor by discounting the future inflows and outflows to their present values.

Hence, the simple methods are somewhat less precise, but in some cases a simple analysis could be sufficient and the only possible alternative while in others it would be preferable to carry out comprehensive analysis using the net present value and the internal rate of return methods

The choice of method depends on the objectives of the enterprise, the economic environment and the availability of data. However, in case two or more projects are being evaluated and compared, the same method consistent with the objectives of the investor should be used to secure a unified base for adequate comparison, final ranking and rational decision making.

Financial analysis is carried out on a year-by-year basis. It includes liquidity and capital structure analysis. The first aims at ensuring the flow of cash through the construction, running-in and operation periods of a project. The capital structure analysis is carried out to make sure that each type of investment (fixed and working capital) is covered by a suitable type of finance.

The framework for the commercial profitability analysis described above is presented in Figure A-1.

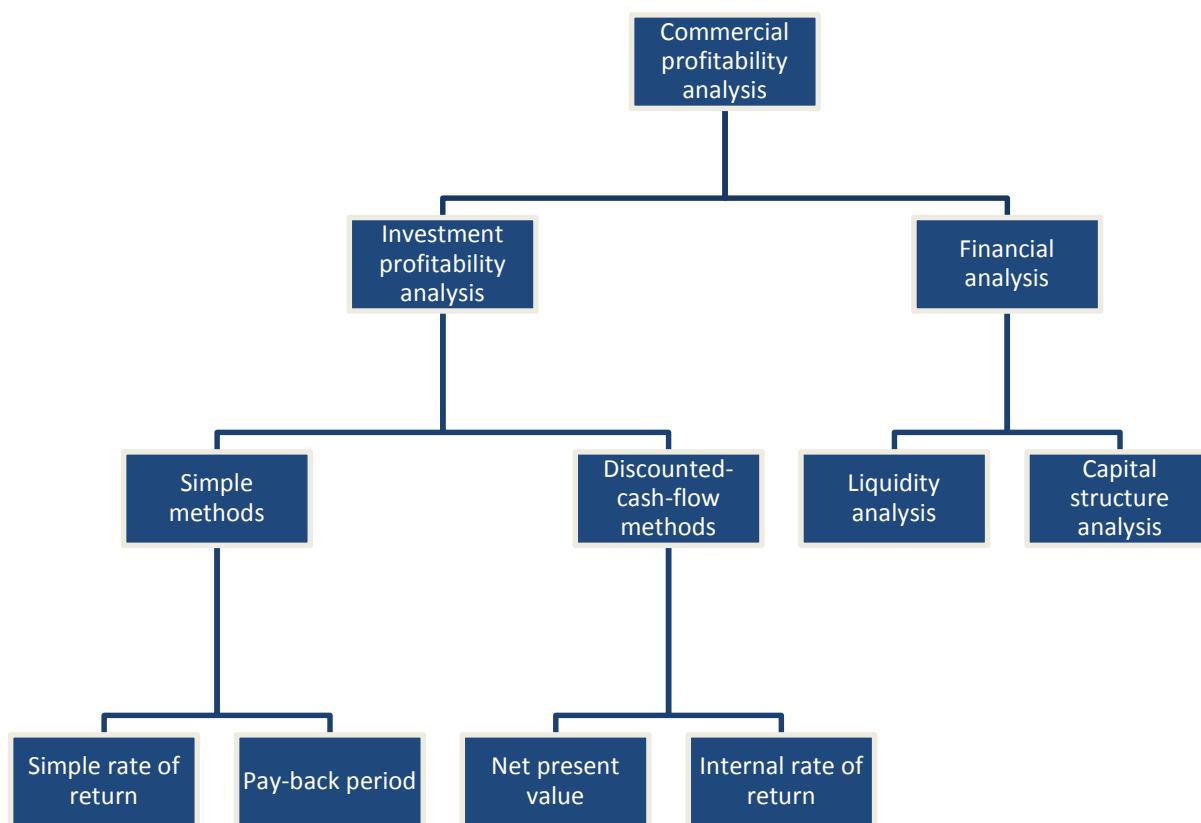


Figure A–1: Framework for commercial profitability analysis

Net Present Value

Net Present Value (NPV) is the difference between the present value of all cash inflows and cash outflows associated with an investment project. The NPV establishes whether or not the investment project is an acceptable investment, given the return the investor requires from the investment. Remer and Nieto (1995) claim that maximizing or minimizing the NPV of a project, depending upon the situation, will provide the most efficiency, and as a result, the most profitability.

In order to calculate the NPV, the interest rate used for discounting the cash flows needs to be determined. The interest rate is often referred to as Minimum Attractive Rate of Return (MARR) and it represents the rate at which the investor can alternatively invest his money, i.e. the return of the most preferable alternative investment. The planning horizon of the project also needs to be determined, and the cash flows for each period of the planning horizon projected (Park, 2002).

The formula for NPV (Park, 2002) is:

$$NPV(i) = \frac{A_0}{(1+i)^0} + \frac{A_1}{(1+i)^1} + \dots + \frac{A_N}{(1+i)^N} = \sum_{n=0}^N \frac{A_n}{(1+i)^n}$$

where

A_n = Net cash flow at the end of period n ;

i = MARR;

N = Service life of the project.

If the $NPV(i)$ is positive for a single project, the project should be accepted, since a positive NPV means that the project has greater equivalent value of inflows than outflows and therefore makes a profit (Park, 2002).

According to Park (2002) the decision rule for NPV is:

If $NPV(i) > 0$, accept the investment;

If $NPV(i) = 0$, remain indifferent to the investment;

If $NPV(i) < 0$, reject the investment.

When comparing mutually exclusive alternatives the one with the greatest positive NPV is selected. According to Remer and Nieto (1995), when comparing alternatives it is important to use the same interest rate for all alternatives. All projects must also be compared over equal time periods, and sometimes adjustments have to be made for to account for this. In the case of mutually exclusive alternatives generating the same revenues, Park (2002) suggests comparing the projects on a cost-only basis. Then the project resulting in the smallest, or least negative, NPV should be accepted, since the objective is to minimize cost (not maximize profits).

Even though the NPV is a widely used criterion for financial feasibility it suffers from two limitations. First, the NPV assumes that periodic cash flows will be reinvested at the discount rate, which in reality is not always possible. Second, when considering two mutually exclusive

projects of unequal size, the criterion's ranking of the projects may give different results than from the Internal Rate of Return criterion, as will be discussed further below (Kierulff, 2008).

Internal Rate of Return

IRR is a concept based on the return on invested capital in terms of a project investment, or as Park (2002) defines it: "IRR is the interest rate charged on the unrecovered project balance of the investment such that, when the project terminates, the unrecovered project balance will be zero. In other words, the investment has zero NPV at this rate of return, noted as i^* . Therefore, i^* serves as a benchmark interest rate, making investors able to accept or reject decision consistent with the NPV analysis. For simple investments, i.e. investments with only one sign change in cash flows, the IRR is the same as the i^* (Park, 2002).

The IRR is equal to the rate of return for which the following function is zero (Park, 2002):

$$NPV(i^*) = \sum_{n=0}^N \frac{A_n}{(1+i)^n} = 0$$

Investors usually want to do better than breaking even in their investments. Their investment policy usually defines a MARR, in which case the IRR and the MARR can be used to decide whether a project is feasible or not. The decision rule for a simple project is as follows:

If $IRR > MARR$, accept the project;

If $IRR = MARR$, remain indifferent;

If $IRR < MARR$, reject the project.

Pay-back period method

This method measures the time needed for a project to recover its total investment through its net cash earnings. Therefore, the pay-back period is the number of years during which a project will accumulate sufficient net cash earnings to cover the amount of its total investment. It is given by the expression:

$$I = \sum_{t=0}^p F_t + D_t$$

where

I = total investment,

p = pay-back period,

F_t = annual net profits in the year t ,

D_t = annual depreciation in the year t ,

$F_t + D_t$ = annual net cash earnings in year t .

If a single project is being evaluated, it will be accepted for implementation in case $p \leq p_m$, where p_m is a cut-off pay-back period adopted by the decision maker. If p is greater than p_m , the project in question will be rejected. The period p_m is usually determined on the basis of past experience and other investment opportunities of the investor and therefore varies largely from case to case. Projects having the shortest pay-back period are accepted in choosing among several alternatives. The pay-back period of a project may be computed in several steps:

Step 1 Compute the total investment of the project, I .

Step 2 Find out the net cash earnings, $F_t + D_t$, for every year during the project's life.

Step 3 Deduct from the total investment the net cash earnings (if any) of the first year of the project's life, which simply means the beginning year of the implementation period. Then proceed to the second, or further to the third or any of the subsequent years, as long as needed for matching the total investment by adding up the annual net cash earnings.

Step 4 Find out the number of the subtractions, which in fact refers to the number of years during which one has to sum up the annual net cash earnings in order to write off entirely the total investment. This number is the pay-back period p expressed in years. The pay-back period includes the construction period.

Step 5 Compare the pay-back period as computed with the cut-off pay-back period set up by the investor. If the pay-back period is shorter than the cut-off pay-back period, the project is acceptable and vice versa. Comparisons should also be made with the pay-back periods computed for alternative investment projects (if any) for ranking purposes.

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