THE IMPACT OF PLATINUM PRODUCTION FROM UG2 ORE ON FERROCHROME PRODUCTION IN SOUTH AFRICA

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ABSTRACT

The South African based platinum mines produce the world's majority of platinum metal that is used in autocatalysts and jewellery. As the platinum market is forecast to grow at healthy rates into the future, the South African producers, Anglo Platinum, Impala, Lonmin and Northam are planning to expand in the next decade. Furthermore a number of smaller producers who are accessing other mineral rights are entering the buoyant market.

The South African platinum mines have traditionally exploited the Merensky reef of the Bushveld Igneous Complex (BIC); however, the mining of this reef is reaching depths that require significant vertical shaft systems and costly refrigeration for access to the ore bodies at deeper levels. In the past decade all of the producers have begun to mine the less attractive UG2 reef because of its cheaper mining costs. This UG2 reef contains significant quantities of chromite with typically a chrome-to-iron (Cr/Fe) ratio of 1.35. UG2 ores can contain between 10 and 25% Cr_2O_3 *depending upon the reef width and the selected mining method. It is relatively cheap and easy to extract a portion of the chromite from a platinum concentrator tailings stream at a grade of between 40-42%* Cr_2O_3*. However it is only in recent years that some ferrochrome producers have begun to source some of their chromite from the tailings of platinum producers.*

South Africa is also the world's largest single producer of ferrochrome and supplies much of the world's stainless steel producers and thus the growing market for their product. As the traditional sources of high Cr/Fe ratio ores have been depleted at the shallow economic depths and thus have become more expensive sources of chromite, technical developments have improved the ability to use fine chromite economically to make acceptable grades of ferrochrome. Thus UG2 fines are now becoming possible cheap sources of acceptable feed to the ferrochrome industry.

The abundance of feedstock for ferrochrome production and the lessening dependence on mined material will impact upon the structure of the ferrochrome business in South Africa. With continued platinum mining from UG2 reefs, South Africa is set to remain highly competitive in the world's ferrochrome/stainless steel industry.

1. INTRODUCTION

The world market for chromites ($FeO \cdot Cr_2O_3$) is driven primarily by the world's demand for ferrochrome use in stainless steels; secondary markets are the chrome chemicals industry, its use in abrasives, refractories and as foundry sand. The largest growth market for chromites has been in ferrochrome production for stainless steels; the secondary markets are all either stable or declining slightly. Especially in the secondary markets there are environmental concerns related to hexavalent chromium (Cr^{6+}). In the refractory market several large international producers have dropped chromite-bearing refractory from their product range and in the wood preservatives market chromated copper arsenate (CCA) is in the process of being banned in the USA [1]. Chrome chemicals in general are likely to be beset by the same concerns [2], and as soon as suitable substitutes become available their use will likely be phased out. However, stainless steel use in the world continues to grow despite occasional slumps in the world economy; typical long-term growth rates of 6-7% are evident for the immediate future with no evidence of a mature market developing and the consequent slowing of growth [3].

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Supply of South African chromites has, as might be expected, moved from the very high-grade deposits of the 1970's to lower grade deposits as the demand volume has increased. Traditionally those mined deposits were sourced from thick chromite seams (preferably 2 meters) to reduce the unit mining costs. In addition, a high Cr/Fe ratio in the basic chromitite mineral (3 at the highest) was sought in order to reduce the unit cost of producing chrome metal as ferrochrome. South Africa's BIC chromite seams are relatively low grade with Cr/Fe ratios of typically 1.7 or less. Early producers exploited reserves with Cr/Fe ratios of >3, but following the advent of the argon oxygen de-carburisation (AOD) process that permitted charge chrome alloy grades (typically 50-52% Cr) to be converted to stainless steel, by the 1980's reserves of Cr/Fe ratios of <2 became the norm. Currently the typical smelter feeds have an approximately 1.5 Cr/Fe ratio but ratio requirements are dropping even further as alloy grades of < 50% Cr (with concomitantly increased Fe credits) have started to become accepted by some customers. During the past two decades this has led to the increasing dominance of South Africa as the geographical source of chromites and ferrochrome, so much so that South Africa is supplying 55% of the world's ferrochrome requirements as well as exporting significant tonnages of chromite concentrates.

Ferrochrome production technology is also changing in response to Cr^{6+} environmental concerns and in response to a decreasing availability of traditional 'lumpy' ore for smelting. New cost-effective techniques for handling fine feeds are being utilised at the more modern installations.

Most South African producers of ferrochrome and chromite for the chrome chemicals market have established the entire vertical integrated structure of resource ownership, mining, mineral processing, smelting and marketing. Competitive advantage was first and foremost in the ownership of the prime resources, then in the modern smelting technology and lastly in the marketing capabilities.

The advent of the Minerals and Petroleum Resource Development Act, no 28 of 2002 [4] and the increasing availability of cheap UG2 resources from the expanding platinum industry are eroding the competitive advantage of the resource ownership; as such competitive advantage now resides in the application of the most cost-competitive pyrometallurgical technology.

2. ORE SUPPLY TO THE FERROCHROME INDUSTRY

Geologically the world's chromite ore resources are found in either podiform or stratiform type deposits. Podiform-type chromite deposits occur in irregular shapes like pods or lenses. Their distribution within a mineralised zone is erratic and unpredictable making exploration and exploitation costly. Economic podiform deposits are located in Turkey, Albania and Kazakhstan. 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 deposit of South Africa's BIC. Lesser such deposits are being exploited in Finland and Zimbabwe; deformed and faulted stratiform deposits are exploited in India, but at exploration and mining costs that must be similar to the podiform deposits [5].

South Africa's reserves are extensive and probably exceed 75% of the world's economic resources. All of these resources are part of the BIC where several chromite seams exist. The economically interesting seams are the LG6 (lower group 6), the MG1/2 (middle group 1 & 2) seams and the UG2 seam (upper group 2). The last of these is not of interest as a source of chromite alone but primarily as a source of platinum group metals (PGMs). As noted for the global chromite resources, within the South African exploitation of the BIC chromite resources historical preference has been for the higher grade and more physically competent seams that produce a lumpy product as represented by the LG6 seams (Cr/Fe ratio of 1.5-2 once beneficiated), followed by the MG1 or 2 seams (Cr/Fe ratio of 1.5-1.8 once beneficiated). Reserve depth, seam width and Cr/Fe ratios, coupled with the preponderance of submerged-arc furnaces (SAFs) dependent on at least a minimum of 30% lumpy ore have been the dominant determining factors in the value of a particular mineral reserve. The lowest grade reefs in the BIC are the UG2 reefs with Cr/Fe ratios of 1.3-1.4; these reefs are primarily exploited in South Africa for their PGM content, although use of UG2 for South African charge chrome production is on the upswing.

The mining of these chrome seams is by conventional scraper-winch and hand held drill rigs where the seams are less than 1.5 meters in width and by more mechanized drill rigs and LHD's where the reef width or combination of closely associated reefs is greater. The mining layout is typically bord and pillar. Only isolated opencast mining is available to most producers now, as many of the outcrops have been mined already. For any resource and chromite ore supply, mining generates material in a range of particle sizes from large lumps to fine sand. Mining of the LG6 and MG1/2 seams produces typically between 5-40% lumpy material that is suitable for smelting in a conventional SAF as well as fines that may be treated by gravity concentration to upgrade the chromite content before pelletising for furnace feed. In ferrochrome production the conventional furnace technology requires a minimum amount of lumpy feed material for practical smelting. Thus most chromite mining operations attempt to maximize the amount of lumpy feed material and to upgrade the fine material either to optimise furnace utilization or to sell fines to the chrome chemicals, foundry and refractory markets. The latter two industries also impose a minimum chromite grain size specification.

Briquetting and pelletising have traditionally been applied to pretreatment of ore fines for ferrochrome smelting. However, the recent application of pelletising and oxidative sintering technology (Outokumpu technology [6]) appears to be cost effective and the preferred method for the pretreatment of fines prior to smelting in South Africa, with no fewer than five such units being installed in the past five years and more in the pipeline. The development of successful fines technologies has removed one of the primary obstacles to UG2 chromite use for ferrochrome production.

Growth in the South African industry has been considerable since the end of the past decade. The past major producers, Samancor, MS&A and Assmang, have been joined by a number of new producers in South Africa such as Xstrata, Hernic Ferrochrome, SA Chrome, ASA Metals and the announced and soon to be constructed Transvaal Ferrochrome. All of these producers have mineral deposits in the LG6 or MG1/2 seams of the BIC but many who have the technology to use a high percentage of fines in the furnace feed are supplementing their furnace charge with chromites from the UG2 seams exploited by the platinum producers.

There are presently two ferrochrome technology routes that can accommodate varying levels of UG2 consumption: (a) the options that utilise pelletising and (b) DC-arc furnace smelting. In terms of pelletising the ore is milled, pelletised and normally sintered to produce a hard, competent pellet that is a suitable replacement for lumpy ore. Technology suppliers such as Outokumpu and Showa Denko typically supply these processes. Both these processes can use UG2 as part of their ore feed to the pelletising plants. In the case of the latter process even more UG2 can be used due to the higher chrome recovery of the process. The pellets are fed in various forms, including pre-reduced, sintered/pre-oxidised, cold or preheated, to a SAF. In terms of DC-arc furnace smelting the process is inherently suitable for the use of UG2 ore. The process is relatively insensitive to the size of its raw material and, due to the relatively high chrome recovery, substantial amounts of UG2 ore can be utilised without the Cr content dropping below the product grade level of 50% Cr. The process operates in an open arc mode, which renders the furnace metallurgy independent of the physical characteristics of the raw materials. Due to the extremely high temperatures within the electrode arc region the reaction kinetics and thermodynamics are enhanced which ensures Cr conversion levels higher than with conventional submerged arc processes, but results in higher energy requirements due to increased heat losses.

2.1 UG2 Ore Characteristics for Ferrochrome Smelting

In order to illustrate the differences between UG2 and typical MG2 and LG6 concentrates the comparative chemical analyses for arbitrarily selected concentrates from UG2, MG2 and LG6 ores are shown (Table 1).

From the comparison below the main differences in the chemical analyses are the Cr reported as Cr_2O_3 and Fe reported as FeO contents, the Cr/Fe ratio and the Ti reported as TiO_2 content. The Cr/Fe ratio is a primary determinant of the Cr grade in the ferrochrome product. For charge chrome the Cr specification is >50%. For particular clients the Ti-content in the ferrochrome (Figure 1) is an important specification, which may require careful control of the ratio of UG2 ore to conventional ore. It is important to appreciate that alloy producers are paid per mass unit of Cr content (in US¢/lb contained Cr), making lower Cr/Fe products less desirable.

Table 1. Typical UG2, MG2 and LG6 chromite ore compositions.

Element/ Species	Cr	"Cr_2O_3"	Fe	"FeO"	Cr/Fe	V	Al_2O_3	MgO	CaO	SiO_2	Ni	TiO_2
	%	%	%	%	ratio	%	%	%	%	%	%	%
LG6 Concentrate	30.2	44.2	18.7	24.1	1.62	0.16	13.8	11.5	<0.3	2.49	0.09	0.53
MG2 Concentrate	29.8	43.6	19.5	25.1	1.53	0.21	14.5	9.56	0.31	2.99	0.09	0.67
UG2 Concentrate	28.5	41.6	21	-	1.36	0.21	15.3	9.62	<0.3	2.88	0.13	0.91

Element/ Species	K_2O	Na_2O	Total C	Gain on Ignition	Loss on Ignition	H_2O	Fe^{3+}	Total S	P	Cl	F
	ppm	ppm	%	%	%	%	%	%	ppm	ppm	%
LG6 Concentrate	30.4	155	0.02	1	-	<0.1	<0.5	<0.01	27	<300	<0.1
MG2 Concentrate	87.5	400	0.03	1.8	-	<0.1	0.13	<0.01	<5	394	<0.1
UG2 Concentrate	57	247	0.05	-	1.6	0.1	0.73	0.01	58	0.40%	<0.1

For typical submerged arc furnace (SAF) production of ferrochrome the Cr recovery ranges between 70% and 80%, which requires a Cr/Fe ratio in the ore >1.5. In the case of DC-arc furnace smelting the Cr recovery increases to 88-92%, which allows the ore Cr/Fe ratio requirement to drop to >1.4. If the Cr/Fe ratio in the UG2 is expected to be below 1.4 (as in the example above) the UG2 ore will need to be blended with another high ratio ore in order to make a ferrochrome product within the specification. In this case a maximum UG2 level of about 70% of the ore feed would be typical. A further advantage of the DC-arc furnace smelting process route is that it inherently yields an alloy of lower Si (typically < 1.5% Si [6]) and Ti content than conventional smelting processes.

In the case of ferrochrome production utilising pellets in a SAF the Cr recovery is expected to be 80-85%, which allows the ore Cr/Fe ratio requirement to drop to >1.45. If the Cr/Fe ratio in the UG2 is expected to be below 1.45 (as in the example above) the furnace will require an increased amount of high ratio ore in order to make a ferrochrome product within specification. In this case a maximum UG2 level of about 40% of the ore requirement would be typical.

Comparative size distributions for arbitrarily selected UG2 and LG6 concentrates are shown in the following table (expressed as % passing size fraction – Table 2).

Table 2. Typical size distributions of UG2, LG6 and MG1 chromite ores (sieve undersize, mass %).

	0.425 mm	0.300 mm	0.212 mm	0.150 mm	0.106 mm	0.075 mm	0.053 mm	0.038 mm
UG2	99.9	99.7	98.7	94.9	85.7	72.2	57.3	44.9
MG1	89.0	81.4	53.7	35.9	16.6	9.0	2.0	0.0
LG6	77.5	65.5	48.0	35.4	18.1	10.0	2.9	0.0

Significant differences in size distributions and grain sizes exist between the three types of concentrates (Tables 2 and 3 and Figures 2, 3 and 4). During transport or unagglomerated use of UG2 in SAFs the fineness results in high handling losses, extraction by the off-gas system and clogging and sintering of the furnace burden.

In the case of the pelletising route, the smaller inherent grain size of the UG2 may theoretically present opportunities for savings in milling costs by the customer in that the ore must in any event still be milled to 80% passing 75 µm, although this depends on the source and type of UG2. A further potential advantage lies in the higher Fe content and inherently smaller grain size of UG2 that is likely to render it more amenable kinetically to oxidative sintering and subsequent carbothermic reduction in the furnace.

Table 3. Chromite average particle sizing.

	LG6 Concentrate	MG2 Concentrate	UG2 Concentrate
Average Diameter, µm	230	190	120
Maximum Diameter, µm	2 300	900	800

Figure 1. Photomicrograph of charge chrome alloy showing some typical Ti-containing inclusions [7] [1,2 = (Cr,Fe) carbide; 3 = σ phase (Cr,Fe) alloy containing 15% Si and 0.2% Ti; 4 = (Cr,Fe) silicide; 5,6 = Ti sulphide (65% Ti); 7 = Ti carbo-nitride (55% Ti)].

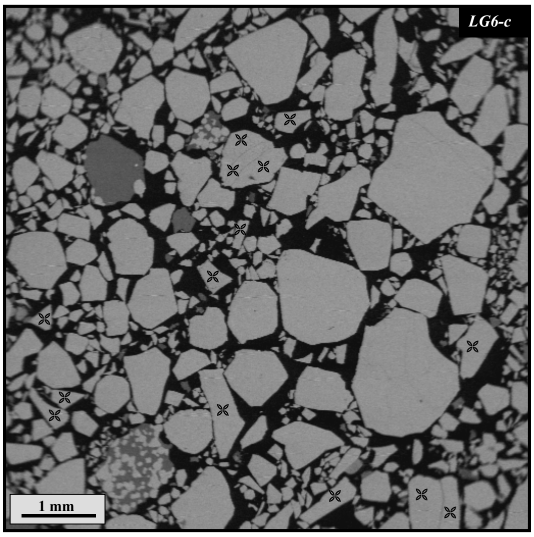

Figure 2. Backscattered-electron image of LG6 concentrate [✕ = fractured chromite particles, Light Grey – chromite, Darker Greys – silicate gangue].

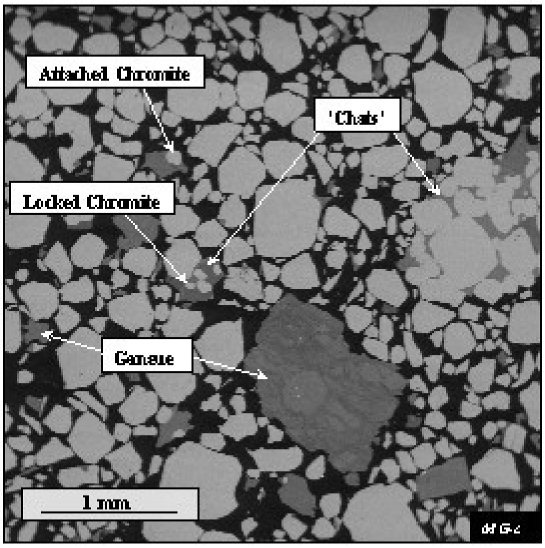

Figure 3. Backscattered-electron image of MG2 concentrate [Light Grey – chromite particles, Darker Greys – silicate gangue particles, Black – mounting resin].

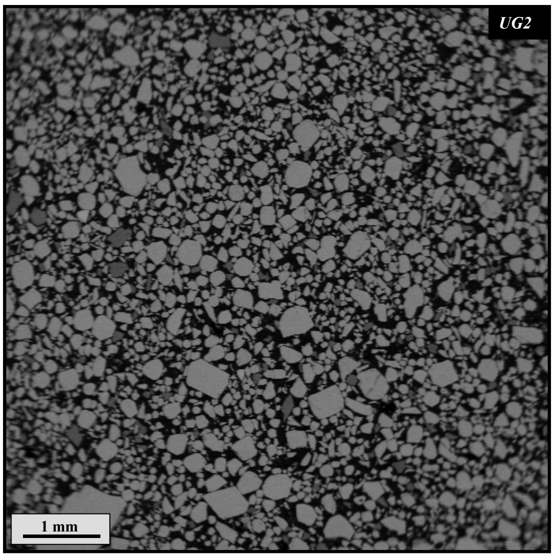

Figure 4. Backscattered-electron image of UG2 concentrate showing well liberated chromite grains [Light Grey – chromite, Darker Greys – silicate gangue, Black – mounting resin].

3. TECHNOLOGY AND MARKET CONSIDERATIONS IN FERROCHROME PRODUCTION

The overall market for chromites is some 15 million tonnes per annum (tpa) of which some 13 million tpa is destined for ferrochrome, primarily used in stainless steel production. Though a reasonably sized market of just less than a million tpa currently exists for the production of chrome chemicals used in timber preservation and other applications, this market will be negatively impacted by recent moves in the USA to ban the use of chromated copper arsenates (CCA) for timber preservation [1]. The stainless steel market has been growing consistently for the past 40 years at an average of 4-5% per annum. Thus it may be reasonable to expect at least similar growth in the chromite market in the foreseeable future leading to new ferrochrome production of 250 000 tpa each year or an additional two large furnaces annually over the longer term. The stainless steel industry has traditionally paid for ferrochrome on the basis of the contained chrome only and has received the associated iron for free. For the bulk of the stainless steel production a 50-52% ferrochrome is an acceptable norm. Thus the ferrochrome industry needs to maximize the chrome output from each particular capital investment in its furnaces to achieve a maximum revenue flow. The output of chrome units is a function of chrome recovery across the pyrometallurgical operation and the alloy grade a function of the Cr/Fe ratios in the feeds. Typical LG6 or MG1/2 ores produce a ferrochrome with >50% chrome whilst the lower UG2 Cr/Fe ratios unsweetened by higher grade ores typically result in only a 48% Cr at best in conventional SAFs. As the Cr/Fe ratio in the BIC chromite is largely fixed in the spinel mineral structure, little can be done from a minerals processing approach to improve the Cr/Fe ratio and iron would need to be rejected either in a hydrometallurgical or pyrometallurgical operation (e.g., selective chlorination of chromite [8]) to improve the Cr/Fe ratio. Both of these approaches to iron rejection would be too expensive currently to be considered economically viable. Hence increasing the chrome recoveries across the pyrometallurgical operations is the only means to influence the maximum chrome content of the final ferrochrome.

Technology has begun to focus on improving recoveries from the typical 70-80% achieved on South African ores with traditional open SAF designs. Essentially three routes have developed; firstly, the pelletising and pretreatment of the pellets, secondly, closed furnace designs that improve the reducing atmosphere and permit more energy-efficient operation with lower furnace offgas temperatures in a more environmentally-friendly manner (less Cr^{6+} emissions) and finally use of the highly reducing atmosphere and open-bath conditions available in DC-arc furnaces.

The Outokumpu process is the best-known pelletising and oxidative sintering technology in the industry [6], but alternatives exist in the DC-arc process (cold, preheated, or pre-reduced fines in fluidised beds followed by DC-arc smelting [9]), the CDR process (direct reduction in a rotary kiln followed by final melting/reduction in a AC or DC furnace [10]) and in the SRC process (fines agglomeration and reduction in a rotary kiln followed by smelting/reduction in a SAF [11]). The CSIR has also tested the as yet untried CSIREX process that uses a tunnel kiln for the pre-reduction of agglomerated fines [12], Inmetco investigated a rotary hearth furnace pre-reduction route [13], while in the mid-80's many Japanese producers studied process routes involving pretreatment followed by smelting-reduction [14,15,16].

These developments have made fines a more acceptable material than chromite concentrate, as the concentrate must first be milled before pelletising in any event. Agglomeration coupled with pre-oxidation (Outokumpu technology) or pre-reduction (e.g., SRC technology) and preheating of the chromite concentrate drastically reduces the required electrical energy for the pyrometallurgical process and in the optimistic scenario could reduce what is the main cost element of ferrochrome production by up to 50% (< 2MWh/t alloy). The specific consumption of another very costly element of ferrochrome production, the reductant itself, can also be minimized through the use of the newer technologies. With pelletising operations or with DC-arc furnaces the choice of reductant is widened and cheaper coals and/or anthracites can be utilized as an alternative to coke. These technologies are opening the doors to the lower grade UG2 concentrates and making them suitable sources of chromite in some situations.

3.1 South African Ferrochrome Production Capacity

South Africa has almost fifty ferrochrome furnaces in close proximity to the BIC. These utilize various technologies from the conventional open SAFs for direct smelting of run-of-mine quality chromite ore to expensive pelletising and sintering plants producing a pre-oxidised pellet fed preheated to closed SAFs or even hollow-electrode direct fines feed to DC-arc furnaces. The following summarizes the ferrochrome facilities by South African producers and indicates the technology applied (Table 4).

Table 4. South African Installed Capacity for Production of Ferrochrome Alloys.

Production Unit	MVA Rating	Capacity (tpa)			
		Charge Chrome	Ferro-silico-chrome	Medium Carbon Ferrochrome	Low Carbon Ferrochrome
Samancor					
Ferrometals		480 000		70 000	
F1 semi-closed SAF	25				
F2 semi-closed SAF	25				
F3 semi-closed SAF	36				
F4 closed SAF (incl. preheater)	63				
F5 closed SAF (incl. preheater)	63				
F6 closed SAF	48				
Pelletising and sintering plant	520ktpa				
CLU converter (MCFeCr)	30t				
Alloy recovery plant (ARP)					
Middelburg Ferrochrome		240 000	26 000		45 000
M1 semi-closed SAF	48				
M2 semi-closed SAF	48				
M3 closed DCAF	63				
CDR kiln (direct prereduction)					
Alloy recovery plant (ARP)					
B open SAF (FeSiCr)	10.5				
C open SAF (FeSiCr)	10.5				
OAF lime-ore melt	18				
Tubatse Ferrochrome		360 000			
T1 semi-closed SAF	30				
T2 semi-closed SAF	30				
T3 semi-closed SAF	30				
T4 semi-closed SAF	37				
T5 semi-closed SAF	37				
T6 semi-closed SAF	37				
Pelletising and sintering plant	350ktpa				
Alloy recovery plant (ARP)					
Palmiet Ferrochrome		130 000			
P1 closed DCAF	40				
P2 semi-closed SAF	20				
P3 semi-closed SAF	20				
Alloy recovery plant (ARP)					
Batlhako Ferrochrome		25 000			
B1 open SAF	12.5				
Alloy recovery plant (ARP)					
Wonderkop JV (with Xstrata)		85 000			
F5 semi-closed SAF	45				
Total Samancor capacity		**1 320 000**	**26 000**[1]	**70 000**[2]	**45 000**
Xstrata					
Lydenburg		400 000			
A closed SAF	33				
B closed SAF	33				
C semi-closed SAF	33				
D semi-closed SAF	38				
2 SDK reduction kilns					
Pelletising and prereduction	300ktpa				
Alloy recovery plant (ARP)					
Rustenburg		430 000			
A semi-closed SAF	33				
B semi-closed SAF	33				
F1 semi-closed SAF	33				
F2 semi-closed SAF	33				

Production Unit	MVA Rating	Capacity (tpa)			
		Charge Chrome	Ferro-silico-chrome	Medium Carbon Ferrochrome	Low Carbon Ferrochrome
F3 semi-closed SAF	33				
F4 semi-closed SAF	45				
Alloy recovery plant (ARP)					
Wonderkop		460 000			
F1 semi-closed SAF	45				
F2 semi-closed SAF	45				
F3 semi-closed SAF	45				
F4 semi-closed SAF	45				
F6 semi-closed SAF	45				
Alloy recovery plant (ARP)					
Total Xstrata capacity		**1 290 000**			
Hernic Ferrochrome					
F1 semi-closed SAF	37				
F2 semi-closed SAF	37				
F3 closed SAF (incl. preheater)	54				
Pelletising and sintering plant	350ktpa				
Alloy recovery plant (ARP)					
Total Hernic FeCr capacity		**260 000**			
Assmang Chrome					
F2 semi-closed SAF	30				
F3 semi-closed SAF	30				
F5 semi-closed SAF	24				
F1 closed SAF (incl. preheater)	54				
Pelletising and sintering plant	350ktpa				
Alloy recovery plant (ARP)					
Total Assmang Cr capacity		**300 000**			
ASA Metals					
F1 semi-closed SAF	33				
F2 semi-closed SAF (in progress)	45				
Alloy recovery plant (ARP)					
Total ASA Metals capacity		**125 000**			
SA Chrome					
F2 closed SAF (incl. preheater)	60				
F3 closed SAF (incl. preheater)	60				
Pelletising and sintering plant	520ktpa				
Total SA Chrome capacity		**240 000**			
TOTAL CAPACITY		**3 535 000**	**26 000**	**70 000**	**45 000**

Notes: [1] Included in low carbon ferrochrome tonnage as feed material
[2] Included in charge chrome tonnage as feed material

3.2 Growth in the Platinum Industry

South Africa is the world's largest producer of platinum. Most of the PGMs are found in the Merensky and UG2 Reefs of the BIC. The reserves of Merensky and UG2 ores, to a depth of 1200 m, have been estimated to be 3 300 million t (Mt) and 5 420 Mt respectively. The UG2 Reef occurs about 150 m below the Merensky Reef in the Western Belt economy and up to 400 m below in the Eastern belt of the BIC. Although rich in chromite [$(Fe,Mg)^{2+}O.\ (Cr,Fe,Al)^{3+}{}_2O_3$], the UG2 Reef is exploited primarily for the PGM value and not for its chromite content.

Despite a generally poor world over the past few years platinum demand has continued to grow. The most significant elements of this growth have been jewellery demand in China, increased use of diesel-propelled vehicles in Europe and growth in computing systems storage capacity. Jewellery demand in China has exploded from only 50 000 ounces of platinum in 1994 to an estimated 1 500 000 ounces in 2002. The popularity of diesel cars in Europe because of improvements to the diesel engine technology has increased demand for platinum in exhaust catalysts; diesel engines require a larger percentage of the traditional three-way (Pt-Pd-Rh) catalyst to be platinum based. High-density data storage discs require a platinum-cobalt alloy for the enhanced magnetic properties that allow greater data storage density; this market has become significant with some 500 000 ounces used annually. In the longer term, from 2010, the use of proton-exchange-membrane (PEM) fuel cells for powering everything from cell phones to buses and hotels holds great promise. Developments have been slow and depend upon the availability of a hydrogen distribution system or reformer technology that can utilize traditional hydrocarbon fuels for hydrogen production. Historical growth in platinum demand is shown below and suggests a continued healthy growth in world demand (Figure 5).

South Africa contains the majority of the world's PGM reserves, some estimates putting South African reserves at 90% of the world's known reserves. All of the major South African producers have announced expansion plans and intend to grow with the continued increase in demand. Anglo Platinum has announced plans to almost double production to 3.5 million ounces by 2006, Impala has the intent of increasing their refined production (including recycled material) to 2.0 million ounces in a similar time frame and finally Lonmin will increase production from some 650 000 ounces to 1.0 million ounces in a similar period. Beyond the major producers a number of juniors will also enter the market (Cluff Mining, Anooraq, Platexco) and some are already in the market (Kroondal Platinum Mines, Mimosa, Zimplats, Southern Era's Messina Mine), although some of these operations have their output reflected in Impala Platinum's refined production forecast.

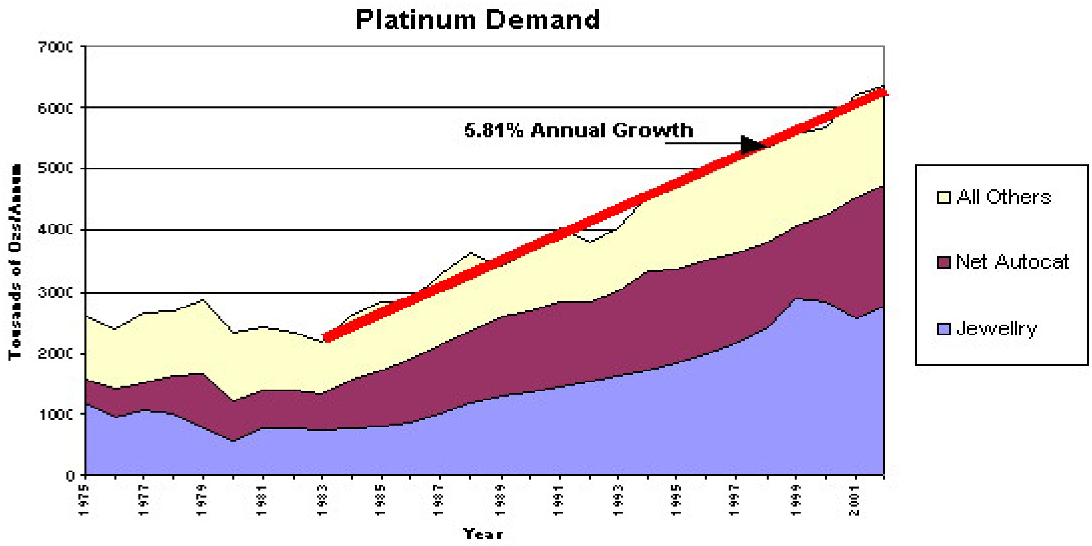

Figure 5. Annual growth in platinum demand by category between 1975 and 2001.

Platinum was first exploited in the Merensky reefs of the BIC because of the higher PGM grade and the higher base metal content; however, for the majority of the producers these deposits are now relatively deep, requiring major investments in shafts systems and refrigeration for exploitation. Thus the UG2 reefs that are low in base metal content and somewhat lower in PGM content are now being exploited to an increasing extent. Since it was first mined in the early 80's, UG2 mining has grown at the expense of Merensky mining such that around 50% of the PGM bearing tonnage mined in South Africa is on the UG2 horizon of the BIC. The expansions mentioned above will be based primarily upon the UG2 reserves of the major producers; it is well known that the Merensky reef on the Eastern Limb of the BIC is often potholed and of lower grade than in the West and that often the UG2 reef is more attractive to mine. The Anglo Platinum announced expansion projects, Twickenham, Paschaskraal and Modikwa, are UG2 based. Similarly, Impala Platinum has initiated its Marula mine and concentrator on the Eastern Limb that is also based on UG2 for its first two phases. In the West the expansions at Rustenburg Section of Anglo Platinum are UG2 based. Thus by 2006 the industry will be mining some 60% of the required tonnage from UG2 reefs and only 40% from the Merensky and Plat reefs.

A generalized map of the BIC shows the major platinum operations and some of the current ferrochrome operations (Figure 6). Ferrochrome operations are concentrated in the Rustenburg and Brits areas with significant production also coming from the Lydenburg and Steelpoort areas, and also feeding ferrochrome smelting operations in Machadodorp, Middelburg and Witbank. UG2 reefs across the BIC are fairly similar in chromite content, with a Cr/Fe ratio of 1.3-1.4 and similar chromite grain sizes. Both in the East and West the chromite mineral is typically 42-43% Cr_2O_3 and 27-28% FeO, the other constituents being about 10% MgO and up to 15% Al_2O_3. Furthermore it is typical to have up to about 1% TiO_2 as rutile, either as attachments or as tiny inclusions contained in the chromite grains [17]. The latter higher TiO_2 content of UG2 in particular may cause some Ti grade problems for some ferrochrome consumers, while the generally low MgO/Al_2O_3 ratios of BIC chromites tends to fundamentally limit smelting chrome recoveries achievable in SAF smelting, relative to some more refractory chromites (where chrome recoveries in excess of 90% are possible).

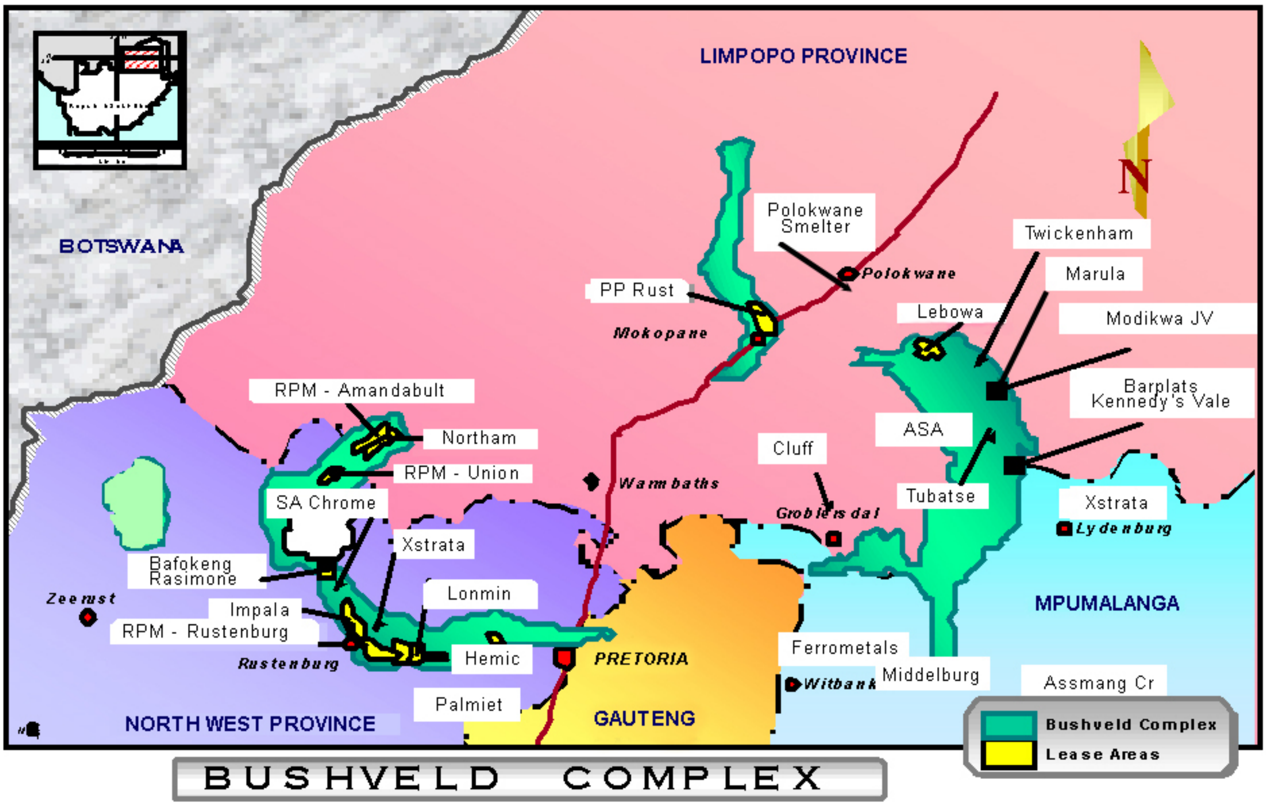

Figure 6. Location of key platinum and ferrochrome operations on the BIC in 2003.

However, the UG2 reef thickness varies across the BIC and when mined the run-of-mine (ROM) ore can have widely varying chromite contents. Reef thickness of only 60-65 cm in the Rustenburg area gives rise to only 12-15% Cr_2O_3 in the UG2 concentrator tailings whilst the mining of thick UG2 seams of 120 to 160 cm in the NW corner of the BIC will provide UG2 tailings with a 25-30% Cr_2O_3 content. Although difficult to project potential chromite concentrate production from the platinum producer expansions without a great deal more detail, some speculative estimates are given based upon the limited knowledge available to the industry (Table 5).

Some small percentage of this concentrate could undoubtedly be skimmed off at a higher grade for sale into the chrome chemicals industry. The remainder could produce as much as seven million tpa of ferrochrome, much more than the market would require for several decades.

Table 5. Estimated potential chromite concentrate production by platinum producers.

Mining Area	Estimated UG2 Mined in 2006 Mtpa	Estimated Maximum UG2 Mining Rate Mtpa	% Cr_2O_3 in ROM ore	Likely Yield from Tailings	Maximum Saleable Chromite Concentrate Mtpa
Western Limb of the BIC					
Northwest	8.1	12.0	26%	30%	3.6
Rustenburg	20.4	28.6	14%	15%	4.3
Brits	13.2	18.0	20%	20%	3.6
Eastern Limb of the BIC					
Northeast	0.6	25.0	20%	20%	5.0
Central	2.4	12.0	20%	20%	2.4
Southeast	3.0	12.0	20%	20%	2.4
Groblersdal	0.0	2.5	15%	15%	0.4
Total		**110.1**			**21.7 @ 41-42% Cr_2O_3**

4. THE FERROCHROME INDUSTRY AS A BUSINESS

The ferrochrome production industry has shifted from the higher cost producers in the developed countries to the developing countries of South Africa and Kazakhstan where extensive chromite ore deposits exist. This is a natural tendency as commodity production moves down the cost curve. Because the ferrochrome business is directly linked to the stainless steel business and this market is based to a large degree upon the construction industry, the ferrochrome business cycles with global growth. Moreover the cycle is frequently accentuated by the recycle of stainless steel scrap that is often more readily available during an economic downturn. Overlying the cycles has been a consistent fall in the real prices of ferrochrome as shown below (Figure 7) that has demanded efficiency improvements in the industry.

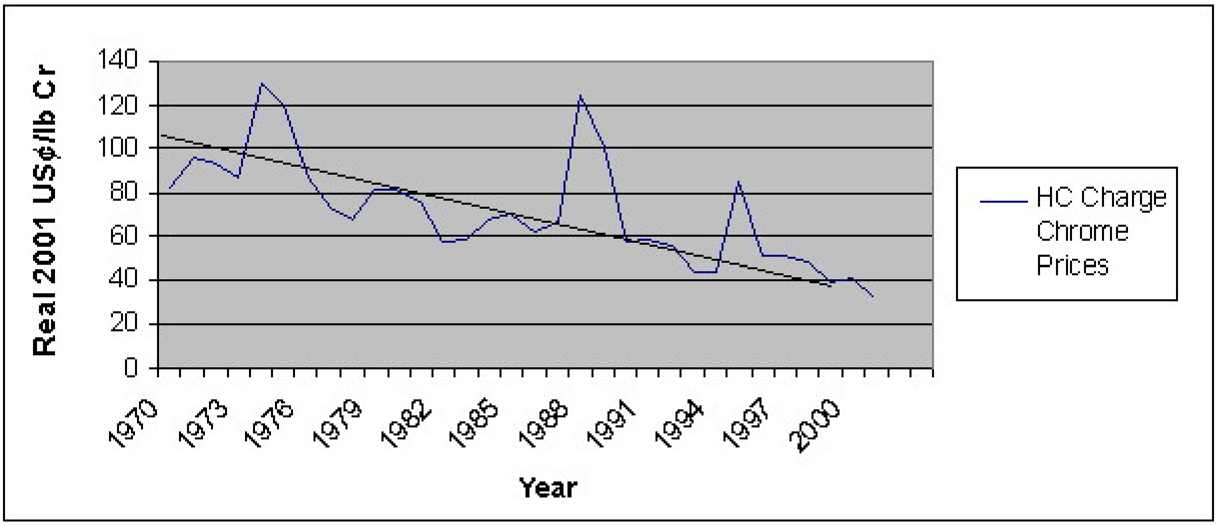

Figure 7. Real decline in charge chrome prices since 1970 [18].

The ferrochrome industry cost structure has been estimated previously [5] and although the mining costs for LG6 and MG1/2 have undoubtedly increased in the past five years and will continue to do so, mining costs remain a relatively low percentage of overall costs (25-35%). Direct comparison to UG2 where mining costs are essentially zero (as a by-product of platinum mining) fails to represent the entire picture. The costs of fines treatment and the chrome recovery potential must be considered, as must the costs of transporting and exporting "free" iron units in a ferrochrome product for which the price is based entirely on contained Cr units. Pelletising and sintering costs can easily offset the reduced mining costs that are a result of UG2 use.

The key lies in increased chrome recovery across the whole of the pyrometallurgical operation so as to make the largest ferrochrome output from a t of chromite concentrate. Poor chrome recoveries and environmental concerns related to Cr^{6+} associated with ferrochrome smelting in conventional open SAFs render their future selection as a technology option somewhat unlikely. Given the same technologies for processing LG6 and MG1/2 however, the differences between UG2 and LG6 and MG1/2 as feed sources are simplistically reduced to the following (for the pelletising route) on the basis of a chrome unit in the product:

When LG6 or MG1/2 Mining + Fines Pelletising Costs > UG2 Mining (payment to Pt producers) + Pelletising Costs by a margin that justifies the loss of revenue for the lower grade ferrochrome produced, then producers will buy UG2 from the platinum producers. Typically there is some 8% loss in revenue (48%Cr/52%Cr = 0.923) or at $0.35/lb contained chrome that equates to R100/t of chromite concentrate. This is the breakeven LG6 or MG1/2 cost; at incremental mining and minerals processing costs >R100/t of LG6 or MG1/2 fines UG2 fines become attractive. This lies in the lower end of the cost curve for mining LG6 or MG1/2 as some are mining at >R150/t; thus UG2 ores are becoming more competitive.

A further complexity lies in the seemingly reverse logic of this market; as the $ price for ferrochrome increases and/or the R/$ exchange rate increases so does the loss in revenue that occurs in utilizing UG2 ores. Thus the producers are driven to maximize the mining and use of the higher Cr/Fe ratio LG6 and MG1/2 ores when times are good for the industry and maximum output is needed, but when times are hard and margins thin the use of UG2 ore is more likely.

Thus where a ferrochrome producer has the flexibility there will be a tendency to husband the LG6 and MG1/2 resources for more profitable times whilst securing UG2 sources at the lowest possible prices for the lean periods. Of major importance to the use of UG2 ore is the minimization of any transport costs. Given the inherent poorer Cr/Fe ratios and the impact upon revenue even a small additional transport cost quickly places the UG2 outside of the market possibility. Geographical placement of any ferrochrome operation that intends to utilize UG2 chromites is critical and must be very close to the UG2 source.

The new Minerals Act [4] promulgated in 2002 in South Africa cedes all mineral rights to the State and opens up mineral resources to all comers. It will no longer be possible to maintain dormant mineral resources without exploiting them as the ‘use it or lose’ principle will be applied. Thus LG6 and MG1/2 rights will become more readily available as well as large amounts of ‘waste’ UG2. This means that reserves are no longer of the same strategic value as previously, but what will be important are reserves that are close to the pyrometallurgical operations and close to other raw material sources and infrastructure for the transport of ferrochrome to the coast for export. Fundamentally the longer term benefit of UG2 compared to newly mined MG and LG ores will progressively increase due to fact that UG2 is a by-product of PGM mining and whilst the costs of gravity concentration will increase over time, they are unlikely to increase at the same rate as LG6 or MG1/2 mining costs. This will result in an ever-increasing gap in the price at which chrome units from these two different sources will be available.

5. CONCLUSIONS AND FORECASTS

Even before the promulgation of the Minerals Act [4] the value of untapped LG6 and MG1/2 chromite resources was falling because of the availability of UG2 chromites and the technical improvements for handling fines and improving chrome recoveries in ferrochrome smelting. The blending of UG2 with LG6 or MG1/2 concentrates is becoming more common practice and the lower grade ferrochrome (<50% Cr) is gradually being more readily accepted by some, although not all, of the stainless steel industry. However, there will always be a large driver for the use of higher-grade (Cr/Fe ratio) ores so as to maximize the output from any particular capital investment and hence the revenue flows. This pressure will be greatest in times of high ferrochrome prices. Thus the best grades will be saved during low price periods and UG2 ores used; the reverse will be true during high price periods. Ultimately the cost of mining deeper LG6 and MG1/2 ores and the wide availability of an estimated 20 million tpa of UG2 chrome concentrates will increase the use of UG2 ores at all price levels.

It can be concluded that in the future most competitive ferrochrome operations will be located adjacent to platinum UG2 concentrators and still relatively close to LG6 or MG1/2 “sweetener” resources. Where such combinations are possible, the traditional ore sources will be at a premium. Technology to handle fine material and to pre-treat the charge to the main smelting furnace will be applied so as to keep costs low and recoveries high. The older conventional open SAFs will give way to closed furnaces and/or DC-arc furnaces largely for reasons of reduced Cr^{6+}, CO_2 environmental output and decreased specific electrical energy requirement. Improvements in the new pelletising and sintering technology will continue to lower operating and capital costs. Declining ferrochrome prices in real terms will continue to place pressure on optimum cost-effective sourcing of cheaper chromite ores including the UG2 by-product from expansions in the platinum industry.

The chrome chemicals market, although small in comparison to the ferrochrome market (roughly 10% of consumption), is an important export market for chromite concentrates. In these markets, the Cr/Fe ratio is of little importance, but what is critical to the economics of chrome chemical manufacture is the silicate content of the concentrates. Most chrome chemical manufacturers would prefer a concentrate with less than 0.5% SiO_2. Higher silica concentrations consume caustic soda in the production of sodium dichromate and lead to practical problems in the kiln operation. The UG2 concentrates can meet these criteria albeit at very low recoveries from the UG2 tailings stream; thus there is some potential for developing this market.

In conclusion it can be stated with some certainty that chromite from UG2 sources will increasingly find application in the production of ferrochrome in South Africa. This increase will primarily be driven by ferrochrome process adjustments to accommodate its limitations of fineness and low Cr/Fe, as well as the low cost base for the conversion of UG2 tailings to usable chromite. There is also significant potential in other markets where conventional chromites are presently used.

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